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VIBRATORY COMPACTION OF AGRICULTURAL SOILS

by



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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

EDMONTON, ALBERTA

FALL, 1972

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Vibratory Compaction of Agricultural Soils" submitted by Jai Singh Parihar in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The primary objective of this project was to investigate the feasibility of using a vibratory compactor to obtain desired soil density gradients for agricultural soils in a laboratory soil bin without soil removal. A vibratory compactor or vibrator was designed and fabricated for the project incorporating a special arrangement for transferring soil over the compacting plate. Soil densities obtained with the vibrator were dependent on the soil type, moisture content, thickness of the compacted soil layer, number of vibrator passes and the amplitude of vibration. It is suggested that there may be a field use for vibratory compaction of seed bed preparation. Measurements of the frequency and amplitude of vibration were made to arrive at a prediction equation for the soil density. However, the narrow frequency range used in the experiment limited the relationship to density and amplitude. Statistical methods of analysis of variance and multiple regression were used to analyse the data. The former identified a density gradient symmetrical with the centre of the sampled soil block (boundary effect) across the width of the soil bin similar to that which occurs with a roller.

ACKNOWLEDGEMENTS

The author wishes to express acknowledgements to

Dr. H.P. Harrison, supervisor,

Dr. R.T. Hardin, statistical advice,

Miss E. Symons, typist, and

financial assistance provided for the project by the J. MacGregor
Smith Scholarship and the Department of Agricultural Engineering,
University of Alberta.

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Chapter 1

INTRODUCTION

Agriculture is an ancient practice. When primitive man turned from a hunting to an agricultural society, he apprehended the importance of tillage which is now one of the world's largest material handling operations. Cultivating implements have been developed on the basis of field experience rather than on a knowledge of soil failure criteria. As a result, tillage tools frequently use an excessive amount of power. Other means of transmitting energy to the soil, such as vibratory tillage, may indicate future possibilities for a more efficient use of power (24).

There are a number of difficulties in the field study of tillage tools. Some of these are the variability of soil texture, the time required to transport equipment to different sites and delays due to adverse weather conditions. Although laboratory experiments using a soil bin eliminate many of these difficulties, density gradients similar to those found in the field are difficult to obtain. Soil density gradients in the field usually increase with depth. When the soil surface is rolled, however, a density profile which diminishes with depth is produced (35).

Agricultural soils are sometimes intentionally compacted. Soil is packed below the seed to give the seedling a firm footing for penetrating the surface crusts (9). Soil is compacted around the seeds as well for better germination. Soil clods are broken to form a fine seedbed and the moist soil is pressed into intimate contact with the seeds so that they can absorb the moisture (12). In sandy soils,

a compacted layer may be created below the tillage depth to reduce the rate of internal drainage. Because the retained water is available for the crop, intentional compaction may have a possible use in dry land agriculture.

The expenditure of time and money on the manipulation of agricultural soils is such that investigations of the processes used are usually rewarding. In particular, methods to achieve specified soil densities and density gradients appear to be a promising research area. Because of the difficulties inherent in a field study, a laboratory investigation of vibratory compaction would appear to provide, at least for the moment, the best return for time and effort.

Chapter 2

LITERATURE REVIEW

2.1 Soil Compaction

Soil has been used as a construction material for thousands of years and soil compaction has long been of interest to civil engineers in designing earth dams and foundations. Compaction increases the soil strength which is generally desirable in engineering practice but undesirable for crop growth because root growth decreases as soil strength increases (52). In the last two decades agricultural engineers have become more aware of the compaction problem of agricultural soils and its effect on crop yield.

2.1.1 Effects of Soil Compaction

Raney (40), in a summary of the effects of soil compaction, states that compaction;

1. changes the content and transmission of water in a soil by altering the void size distribution,
2. alters the transfer of gases within a soil and between a soil and the atmosphere by changing the size of the air filled pores,
3. affects the content and transmission of heat in a soil by changing the soil density,
4. modifies the rate of nutrient movement to the roots by altering the rate of diffusion and mass flow and also the amounts of nutrients mineralized from the soil organic matter.

2.1.2 Mechanical Impedance

Eavis (18), experimenting with peas, suggested that root

extension can be limited by the mechanical impedance of the soil. Morton et al (37), in an experiment involving seedling emergence, found that applying a surface compaction pressure in excess of 0.5 p s i supressed seedling emergence. Abdalla et al (2) concluded that within limits of mechanical impedance, roots can penetrate a soil by radial thickening which reduces the soil resistance to axial elongation.

Intentional soil compaction is done to compact soil around seeds for better germination. The soil clods are broken to form a fine seed bed and the soil is pressed into intimate contact with the seeds so that they can absorb moisture from the soil particles (12). Carnes (9) concluded that the soil should be packed below the seed in order to give the seedling a firm footing for penetrating the surface crust. Stout et al (46) found that, when pressures were applied at seed level, seedling emergence improved but when pressures were applied on the surface of the soil 1 inch above the seed, emergence decreased.

Carnes (9) asserted that compaction below the seed level also improves the moisture retention and thereby make more water available to the plants. Cooper (12) alleged the same for sandy soils. Hyder and Bement (25) built a microridge roller which packed sandy soils into ridges, thus reducing wind erosion and moisture loss during germination and the seedling stage.

2.2 Mechanics of Soil Compaction

Soil may be described as a skeleton of solid particles enclosing voids which may be filled with a gas or liquid (23). A change in the state of compaction results from a change in the volume of the soil.

According to Harris (23) there are four possible factors to which the change could be attributed. They are;

1. a compression of the solid particles,
2. a compression of the liquid and gas within the pore spaces,
3. a change in liquid and gas contents within the pore spaces,
4. a rearrangement of the soil particles.

For these four factors, Harris did not appear to have considered consolidation in which dissipation of liquid also takes place. The time required for consolidation, however, is much longer than that usually associated with the manipulation of agricultural soils.

The solid particles and the liquids are virtually incompressible and do not undergo appreciable volume change when subjected to typical loads in agriculture. The change in the state of compaction, therefore, depends on movement of the liquid, gas and the solid phase and can be expressed as a change in the soil parameters of the void ratio, porosity and the bulk density. These soil parameters are defined as follows (23);

$$\text{Porosity (n)} = \frac{V_v}{V}$$

$$\text{Void ratio (e)} = \frac{V_v}{V_s}$$

$$\text{Dry bulk density (D}_B\text{)} = \frac{W_s}{V}$$

where,

V_v = volume of pore space

V = total volume

V_s = volume of solids

W_s = weight of oven dry solids.

Soil compaction has been defined in a number of ways. According to Soane (42), compaction is a process in which the rapid application of a load results in the increase of soil dry bulk density and an associated decrease of air filled porosity without a change in moisture content. Cooper and Nichols (13) define compaction as an increase in the soil bulk density by a reduction in its pore space.

According to Sowers and Sowers (43), "Densification or a reduction in the void ratio, occurs in a number of ways: reorientation of the soil particles; fracture of the particles or the bonds between them, followed by reorientation; and bending or distortion of the particles." Breunich (7) stated that intergranular friction must be overcome if the soil is to be compacted. This is usually done by applying a force to cause crushing, sliding, and shearing of the particles. Energy consumed in this process is supplied by the 'compactive effort' of the compacting device. The effectiveness or efficiency of the compactive effort depends on the type of soil particles and on the way in which the effort is applied.

The process of densification is further explained by Sowers and Sowers (43) "In an unsaturated cohesive soil the densification is primarily accomplished by distortion and reorientation, both of which are resisted by the interparticle attractive force of 'cohesion'. As

the water content of the soil is increased, the cohesion is decreased, the resistance becomes less, and the effort becomes more effective. In an unsaturated cohesionless soil, the densification is attained primarily by reorientation of the grains, although fracture of the particles at their point of contact is an important secondary factor. The reorientation is resisted by the friction between the particles. Capillary tension of the moisture films between the grains increases the contact pressures and increases the friction. If the moisture content is further increased, the capillary tension decreases and the effort becomes more effective." For saturated conditions, Harris (23) asserted that a large change in volume is a function of the rate at which liquid moves in the soil mass. According to this author ... "the state of compaction can be completely specified by giving the dry bulk density. The bulk density can be related to porosity and void ratio which have more meaning."

The factors that appear to affect soil compaction are;

1. moisture content
2. soil texture
3. compaction effort
4. initial density.

2.2.1 Soil Compaction vs Moisture Content

The basic principles of soil compaction were first defined by Proctor (39). He found that, for every soil and compactive effort, the density is a function of water content and there exists an optimum moisture content at which dry density is a maximum. Various explanations have been given for the relationship between dry density and moisture content (26,43,54). For example, Wu (54) has written

"Beginning at low water content, the degree of compaction of the soil increases with an increasing amount of moisture. This is because the added moisture serves to render the soil more plastic and workable and facilitates the compaction process."* Therefore, in this range the dry density increases with the water content. However, after reaching a maximum the dry density drops with a further increase in moisture. At this state soil is near saturation and further compaction is therefore ineffective since there is little or no air void left in the soil.

It is important to recognize an interaction of soil texture and water with respect to compaction. Wu (54) stated that the effect of moisture is rather pronounced in cohesive soils and relatively unimportant in cohesionless soils.

2.2.2 Soil Compaction vs Soil Texture

The maximum dry density and the optimum water content varies with the soil type. Wu (54) remarked that the value of the maximum dry density is dependent to a large extent on the particle size distribution. Well graded or evenly distributed particle sized soils can be compacted to higher dry densities than soils with poor gradation.

2.2.3 Soil Compaction vs Compactive Effort

Sowers and Sowers (43) asserted that the greater the

* It should be recognized that the water is added prior to compacting the soil, not afterwards.

compactive effort, the higher the maximum density and the lower the optimum moisture content will be. In general, Djokoto et al (15), observed that an increase in the packer weight resulted in an increase in dry bulk density. Sowers and Sowers (43) stated that type of effort is also important. Vibration, which he contends reduces the friction between the particles, is particularly effective in compacting a cohesionless soil but for a cohesive soil, pressure that bends and forces the particles into new positions is better.

It is also evident that the duration of the compactive effort is a factor in the density obtained. Alboaba (3), in a study of the duration of compaction, established that compaction of a soil was reduced as the travel rate of a roller was increased. Similarly, Vomocil et al (51) found that, at high speeds, the compaction caused by tractor wheels was reduced. In comparison with moisture content, however, the response to speed was limited.

2.2.4 Soil Compaction vs Initial Density

Djokoto et al (15), found no correlation between the bulk densities for a clay loam soil before and after using agricultural-type packers. As Djokoto et al cultivated the soil before compaction, the observation is limited to low initial densities. Pettibone and Hardin (38), in their vibratory compaction test on cohesionless soils, observed that the initial density did not have a significant effect on the final density obtained. Though only two references have been cited, it is apparent that the initial density is not an important variable in soil compaction.

2.3 Soil Density Profile

According to Maclean (35), the dry density is a non-linear function of the number of passes of the roller over the soil surface.

This author further stated that a density profile, which diminishes with depth, is produced when the soil surface is rolled. It follows from this that, to produce a non or a reverse density gradient, only a portion of the soil should be placed and rolled at one time.

Luth and Wismer (34) were able to compact the subsurface using a vibratory compactor without removing the soil. The compactor incorporated a shear plate so that the vibrating plate could engage the soil at a specified depth. The authors used an electrically driven oscillator to vibrate the compactor plate. The minimum strength of the soil (air dry sand) was obtained by vibrating the compactor plate near the bottom of their soil bin. The observations of Luth and Wismer suggested the possibility of obtaining various desired density gradients using a vibrating compactor.

2.4 Vibratory Soil Compaction Mechanics

Soil compaction by vibration may be defined as the application of a rapidly varying force to the soil through a soil/machine interface. Terzaghi and Peck (47), in their study on the effect of vibrations on soils remarked as follows;

1. At the frequency which is approximately equal to the natural frequency of the vibrator and the vibrating portion of the supporting soil, the amplitude of vibration is maximum and the state is called resonance.
2. The natural frequency increases with increasing density and decreasing compressibility of the soil.
3. The effect of vibration on clays is far less conspicuous than on sand because the cohesive bond between clay particles

interferes with intergranular slippage. Nevertheless, even a soft clay consolidates to a moderate extent when it is continually subjected to intense vibrations having a frequency close to the natural frequency of clay. Pettibone and Hardin (38) agree that vibration at the resonant frequency would be very desirable.

Lewis (33) studied the compaction of soils with vibratory compactors and observed the following;

1. Compaction is a function of the soil type, moisture content, thickness of soil layer and number of passes of the compacting machine.
2. The state of compaction obtained after a given number of passes decreased with depth and an increase in speed of compaction.
3. Changes in the frequency of vibration were not critical for cohesive soils but were significant for granular soils.
4. There must be revision of the belief, such as stated by Terzaghi and Peck (47), that vibratory compactors are suitable only for the compaction of granular soils. For successful compaction of cohesive soils, however, high compacting effort is necessary to compensate for the very short duration of contact.

2.4.1 Vibratory Compaction - Cohesionless Soil

Harrison (24) noted a proposal by Gumenskii and Komorov that sandy soil may be characterized by a "coefficient of vibroviscosity" since soil, when shaken, acquires the properties of a viscous liquid.

These authors advised that the "coefficient of the 'internal friction' of sand is inversely related to frequency". Barker (5) also noted a reduction in the 'internal friction' of sandy soil with frequency when driving piles. Konder and Ayre (29), obtained a maximum penetration of a cone which was associated with a natural frequency of the 'soil-vibration system'.

Pettibone and Hardin (38) concluded for the electromagnetic table-type vibrator that "the amplitude of the vibration was the most significant variable affecting soil density and; "...maximum densities were generally obtained at the higher amplitudes".

2.4.2 Vibratory Compaction - Cohesive Soil

Konder and Edwards (30) experimented with cohesive soil using a cone penetrometer, and wrote; "...soil properties are definitely frequency dependent and their strengths can be greatly reduced by vibration...". Konder (28) draws attention to the fact that the change in soil strength due to vibration is contrary to the response when the soil is subjected to a single-acting, rapidly applied load. He found with vibratory loading that "the soil strength was only one-half to one-fifth of that obtained by the conventional unconfined compression test, depending on the moisture content of the specimen".

As noted on pages 10 and 11 a vibratory compactor is more effective in compacting a cohesionless soil compared to a cohesive soil.

2.5 Measurement of Soil Moisture

The moisture content of soil is the principle factor determining soil mechanical behaviour and moisture measurement is indispensable in studies of soil tillage and compaction. Many methods are available for soil moisture measurement (1,21). These include the neutron scattering,

gamma ray attenuation and gravimetric methods.

Stone et al (45) suggested the method of neutron scattering for moisture measurement. Fast moving neutrons lose some of their energy and are slowed down when they collide with hydrogen atoms. The slowed neutrons are sensed by a detector.

The gamma ray attenuation method, described by Van Bavel et al (48) depends on the fact that gamma rays lose part of their energy upon striking another substance. The non-attenuated gamma rays are sensed by a detector separated from source. A narrow beam of gamma rays can be obtained by shielding the radioactive isotopes source except for a small 'window' and therefore can be used to study moisture in soil layers as thin as 1 cm.

By far the most common is the gravimetric method because it is simple and accurate as compared to neutron scattering and gamma ray attenuation methods. For this method, a known weight of soil sample is placed in an oven at 105°C and dried to a constant weight. The weight difference is considered to be the amount of water that was in the soil and which can be expressed as a percentage of the dry soil weight. A limitation with this method is that it is time consuming requiring at least 24 hours before moisture can be determined.

2.6 Measurement of Soil Density

A number of methods are available for measuring the soil density and are discussed by Blake (6) and Freitag (20). These include the excavation, water displacement, radiation and core methods. For the excavation method, the bulk density is determined by excavating a quantity of soil, drying and weighing the soil and determining the volume of the excavation. The latter could be obtained by the sand cone or rubber

balloon apparatus (6). The disadvantage of this method is that a large sample is required and, therefore, the bulk density of a localized horizon cannot be determined.

For the water displacement method, a soil clod is covered with paraffin and subsequently weighed in air and water. The difference in weight, which is equal to the volume of water displaced, minus the volume of paraffin supplies the volume of the clod. The oven dry weight of the clod is then determined and the bulk density is then calculated. This method gives higher bulk densities because it does not take the inter-clod space into account. As the clod is air-dried before the paraffin covering, the clod volume is less than the field sample.

The radiation method, discussed by Van Bavel et al (49), is useful in making a non-destructive measurement of soil density. By suitable calibration, measurement of the gamma radiation can be used to estimate the bulk density. This method is useful in taking a number of readings in a very short time but has certain limitations such as radiation hazard, cost of equipment and inaccurate densities at the surface of the soil.

The simplest and most widely used method for density measurements is the core method. For this method, a cylindrical metal sampler is pressed or driven into the soil to the desired depth and, if removed carefully, it will remove a soil sample of known volume. The sample is oven dried and the bulk density is the oven-dried weight divided by the sample volume. This method has the advantage that the moisture content can be determined by subtracting the weight of the sample after drying from the weight before drying.

2.7 Penetrometer

Another method of characterizing soil 'strength' is the soil cone Penetrometer. A cone at one end of a driving shaft is pushed into the soil at a uniform rate and the simultaneous measurement of the depth and resistance to penetration can be made. Usually force per unit area of cross-section of cone base is expressed as cone index. Although the relationship between the force used to push the cone into the soil and the physical properties of the soil is complicated and only partially understood, a comparison of penetration resistances between soils is useful in studying compaction.

Penetrometers can be of two types;

1. The push type such as developed by Carter (10) provides a convenient manner of securing a continuous curve of resistance as a function of depth.
2. The impact type permits penetration of hard soil conditions with a relatively light weight unit.

A number of researchers have used the soil cone penetrometer and found a correlation between some soil properties, such as the bulk density, with the cone index. Freitag (19) observed a good correlation between the soil cohesion and cone index when friction angle was near zero (approximately 2° or less).

Domier (16) obtained for Osborne clay soil an increase in resistance to penetration with an increased number of tractor tyre rollings. Maximum resistance occurred in the 1.5 inch to 2 inch region below the surface. Mcleod et al (36) stated that penetrometer readings could be used to detect changes due to compaction from vehicle

traffic if the soil was unsaturated.

Chesness et al (11) asserted that, for Faceville sandy loam soil, remolded samples do not exhibit the same soil strength or resistance to penetration as "in situ" soils and that the bulk density and moisture content parameters are not adequate in describing penetration resistance or soil 'strength'. Maclean (35) et al remarked that remolded or structureless soil may be considerably weaker than an "in situ" soil. Soane (42) argues that "for field investigations the measurement of soil 'strength' with a penetrometer is quick and cheap but gives results dependent on moisture content, the type of equipment and its mode of use".

McLeod et al (36) observed that the rate at which the cone penetrates the soil can affect the pressure required to cause penetration. The author determined that "the general relation obtained in a wet, fine grained soil is that the penetration resistance is relatively low at low speeds and increases rapidly as the speed of penetration increases". At the higher speeds of penetration, the trend appears to level off.

A major problem limiting the use of penetrometers in the field are hidden stones which, if encountered, give non-representative readings for penetration resistance. According to Vomocil (50), bulk density data are more readily interpretable in terms of fundamental soil properties such as porosity than are penetrometer measurements.

2.8 Summary

Soil compaction by vibration suggests the feasibility of obtaining a desired soil density gradient in the laboratory soil bin. This is not possible with a roller without soil removal. Vibratory compaction

may also have a possible application in the field for seed-bed preparation. Vibratory compaction is a function of the soil type, moisture content, thickness of soil layer and the number of passes of the compacting machine. It is also evident from the literature review that a vibratory compactor is more effective in compacting a cohesionless soil as compared to a cohesive soil.

For soil moisture measurements, a gravimetric method is extensively used while a core method is widely used for soil density measurements. A recording cone penetrometer can be used to characterize the soil 'strength' by measuring resistance to penetration of the penetrometer into the soil but has some limitations.

Chapter 3

FACILITIES

The experimental work was carried out using the facilities of the Department of Agricultural Engineering, University of Alberta. The basic equipment was a soil cart, rotary tiller and a vibrator. A penetrometer and a density sampler were used to measure the effects of the vibration. An accelerometer was used to determine the amplitude and frequency of vibration.

3.1 Soil Cart

The box of the soil cart was 10 ft long by 3 3/4 ft wide by 1 1/4 ft deep. The rubber tired wheels of the cart ran on an angle iron track (figure 1). The track length was approximately 30 ft. Two sprockets at each end of the track were connected with a roller-type chain which in turn was connected or fastened to the cart. A 7.5 H.P. electric motor, with a variable speed drive, supplied the torque which in turn was transmitted to one of the sprockets through two automotive-type transmissions. The motion of the soil cart could be reversed by reversing the direction of rotation of the electric motor. Switches at each end of the track limited the cart movement by stopping the electric motor. The controls for the electric motor were conveniently located. Any cart speed from 1.2 m to 13.0 m per minute was available by selecting suitable gear ratios in the automotive-type transmissions and setting of the pitch diameters in the variable speed drive.

3.2 Rotary Tiller

The rotary tiller with a blade diameter of 30 cm and a width of cut of 60 cm was used for soil preparation. The tiller was driven by a 3/4 H.P. electric motor at a rotational speed of 27 rpm. The tiller,



Figure 1: Soil cart and Rotary tiller.

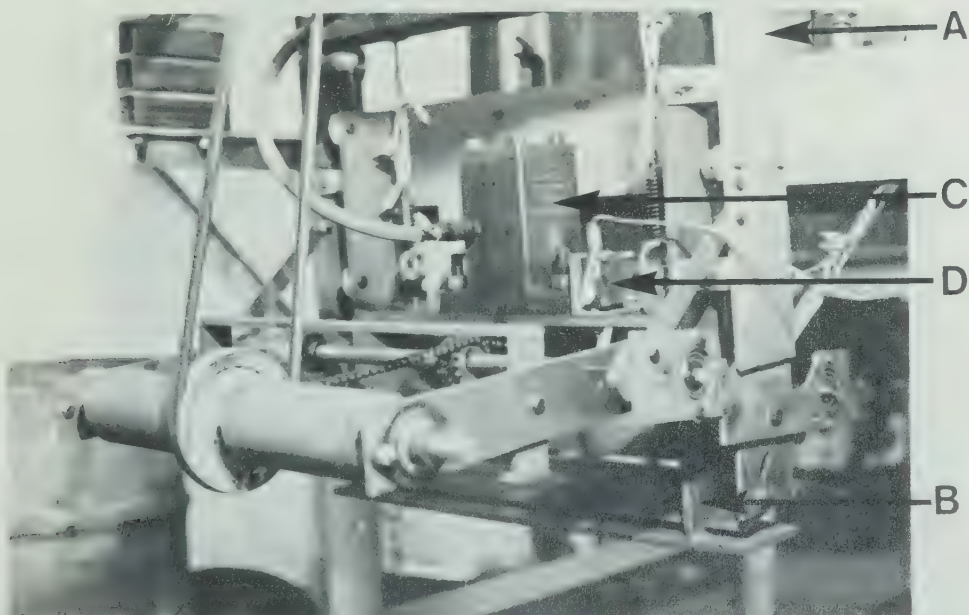


Figure 2: Vibrator - Main Frame (A), Compactor Frame (B), Pneumatic Hammer (C) and Accelerometer (D).

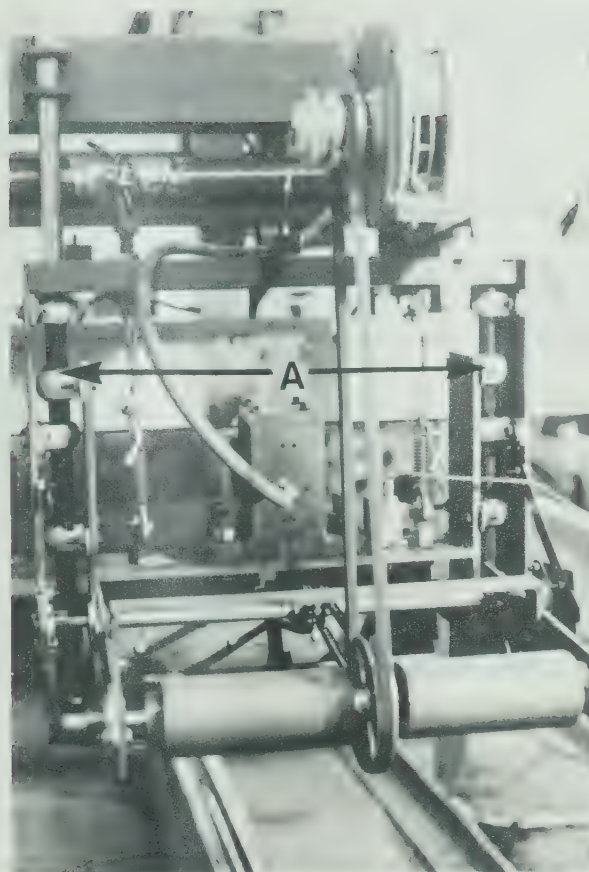


Figure 3: Vibrator - Steel rods slide arrangement (A).

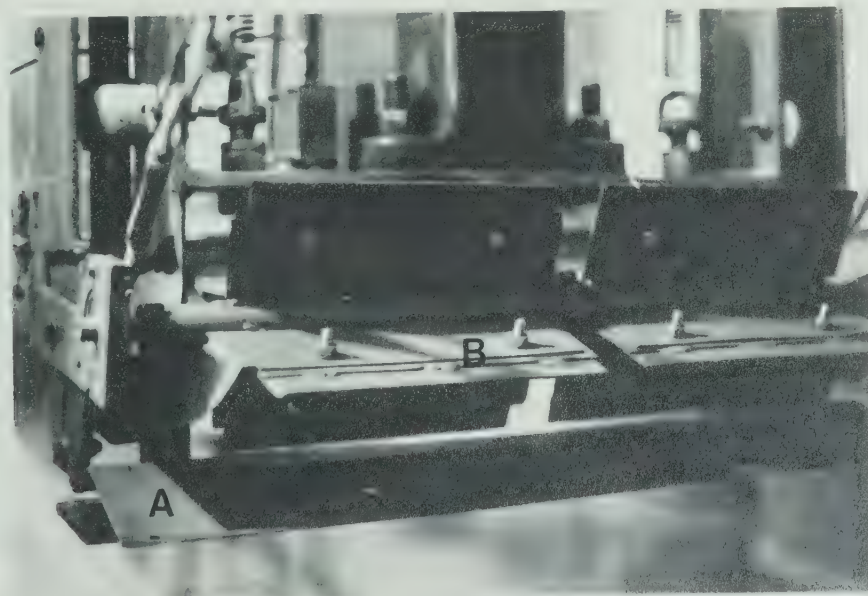


Figure 4: Vibrator - Shear blade (A), Rotor (B).

together with the electric motor; was mounted on a platform (figure 1) which could be raised and lowered with a winch.

3.3 Vibratory Compactor Assembly

The vibratory compactor assembly or vibrator was fabricated for the project utilizing a Cannon Model 222 pneumatic hammer. The hammer weighed 28 lbs. The frequency specification of the hammer was 2850 cpm using 11 cfm of air at 60 psi. The limited size of the hammer necessitated a number of design modifications including a reduction of the soil cart's width to 60 cm.

The final arrangement of the vibrator consisted of a main and a compactor frame (figure 2). The hammer was fastened on the compactor frame which in turn was isolated from the main frame in the vertical plane. The bottom of the compactor frame had a 57 cm long by 10 cm wide compacting plate which engaged the soil. The accelerometer, noted earlier, was mounted on the compactor frame. The compactor frame was suspended by two springs from the main frame. The latter was suspended from a pipe by cables. A winch was utilized to turn the pipe thereby raising or lowering the main and compactor frames. An arrangement of slides and two steel rods restricted the movement of the main and the compactor frames to the vertical plane (figure 3).

The main frame included a shear blade and a small rotor (figure 4). The angle of the shear blade was adjustable and the blade's purpose was to maintain the depth of the compacting plate and to keep the soil above it from dampening the vibrations (figure 5). The rotor was used to facilitate the flow of the soil over the shear blade while the compacting plate engaging a sub surface of soil (Appendix III). The rotor was driven by an adjustable speed electric motor.

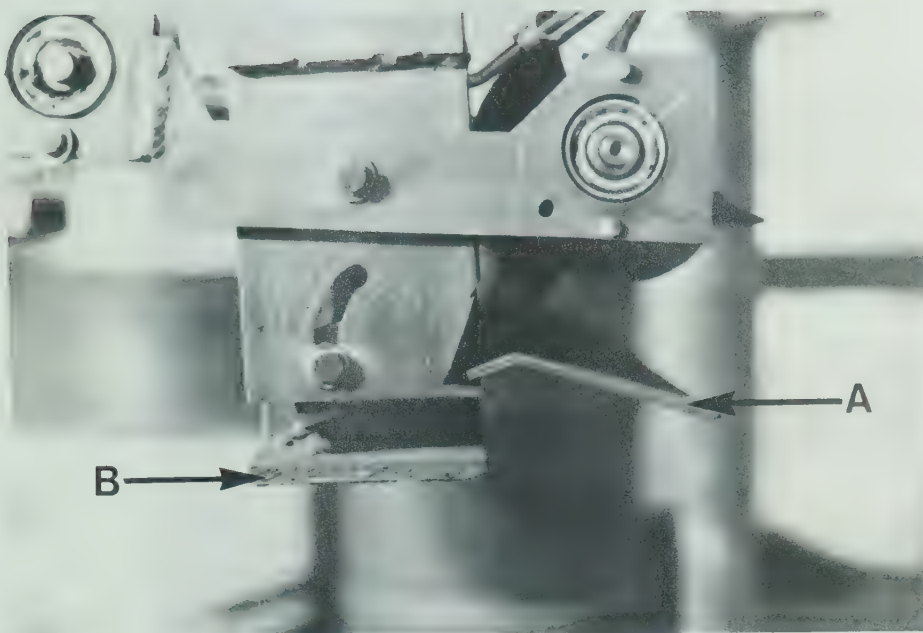


Figure 5: Vibrator - Shear blade (A), Compacting plate (B).

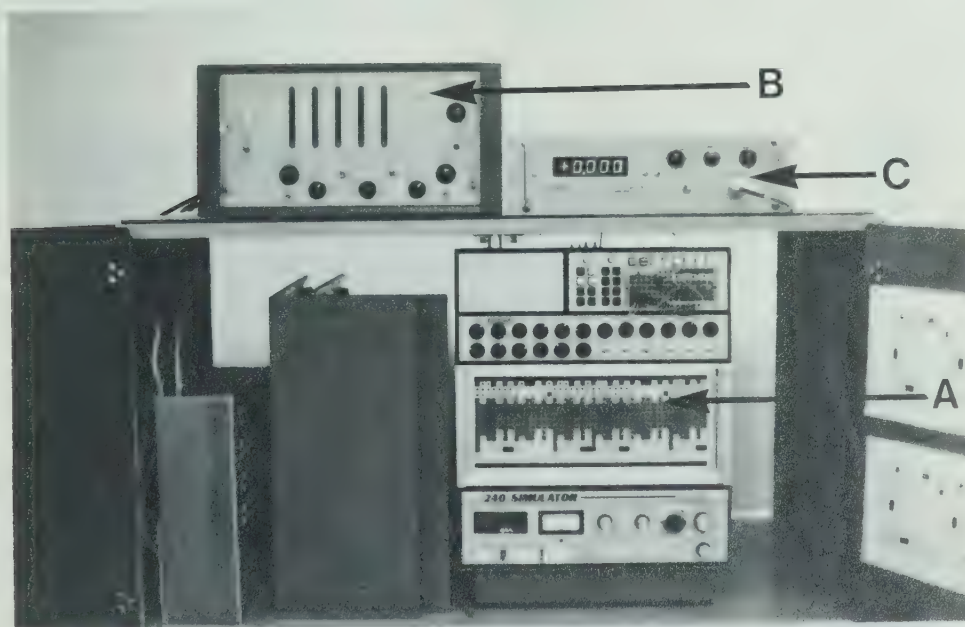


Figure 6: Analog Computer (A), Electronic Counter (B) and Digital Voltmeter (C).



Figure 7: Recording Soil Cone Penetrometer.

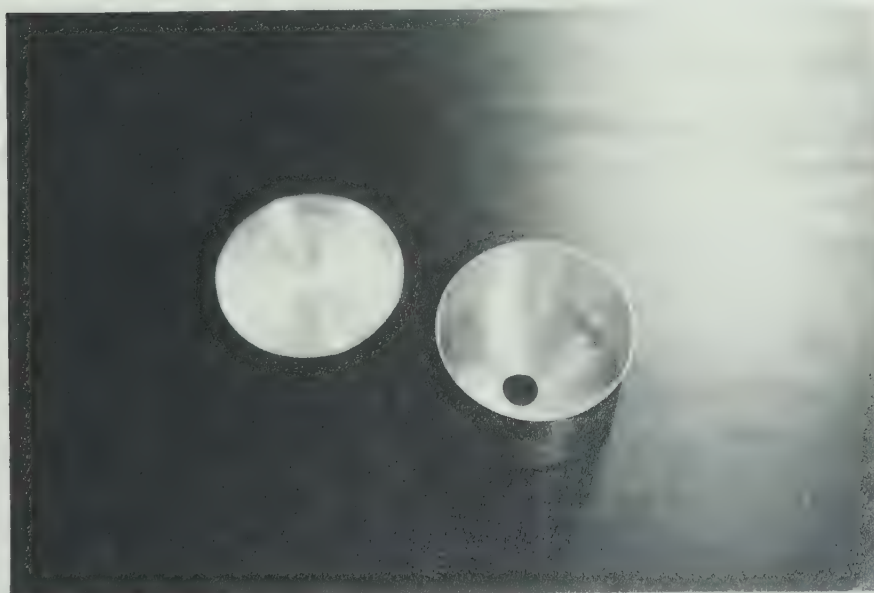


Figure 8: Soil density sampler.

3.4 Data Processing Equipment

The electric signal from the accelerometer (±5 g) was processed by an analog computer (Simulator Model 240D). The amplitude and frequency of vibration were determined from values displayed respectively on a digital Voltmeter (Beckman Model 4011 AR) and an electronic counter (Beckman Model 7050), see figure 6.

3.5 Penetrometer

Some resistance versus depth profiles were obtained with a 30° cone push-type recording soil penetrometer developed by Carter (10), see figure 7. It was found that the penetrometer was insensitive to the density changes obtained with the vibrator and therefore, its use was abandoned.

3.6 Soil Density Sampler

A circular aluminum box with a diameter 6.4 cm and height 4.2 cm was used to take density samples. The hole in the top of the sampler enabled entrapped air to escape (figure 8).

Chapter 4

EXPERIMENTAL DESIGN AND PROCEDURES

The change in the state of soil compaction can be expressed as a change in the soil parameters of the void ratio, porosity and the dry bulk density or dry density. The parameter dry density (D) was chosen as the dependent variable to express the state of soil compaction because it is the most widely used soil parameter. As indicated in the literature review, the independent variables which were expected to influence dry density were the soil type, moisture content, thickness of compacted soil layer or lift thickness and number of passes of the vibrator. In order to include this number of independent variables in the experimental work, only two levels of each were included.

4.1 Soil Properties

The particle size distributions (31) of two agricultural soils, which were taken from the cultivated horizon, were determined (see figure 9). On the basis of a United States Department of Agriculture soil classification (8), the soil textures were silt loam and sandy loam. The two soils were chosen for study because most agricultural soils will fall between them.

The optimum moisture contents for the two soils were determined using the Standard Proctor test (39). Because lower densities than those achieved with the Standard Proctor test were expected with the vibrator, a special test, using a 5 in height of free fall of hammer instead of the standard 12 in, was devised (see figure 10). Two moisture contents, of 16% and 20%, were selected as these were close to the optimum moisture content

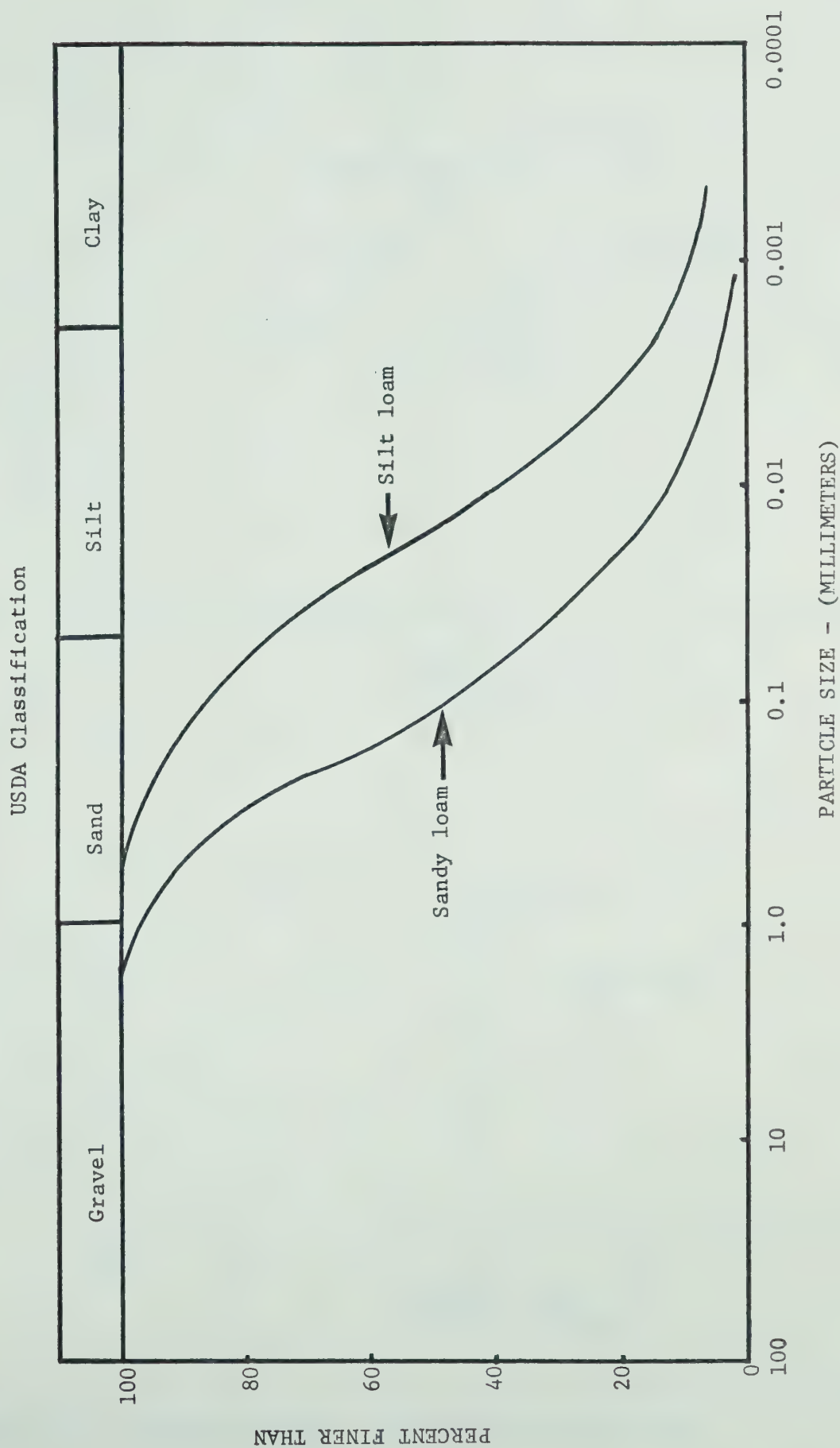


Figure 9: Particle Size Distribution Curves.

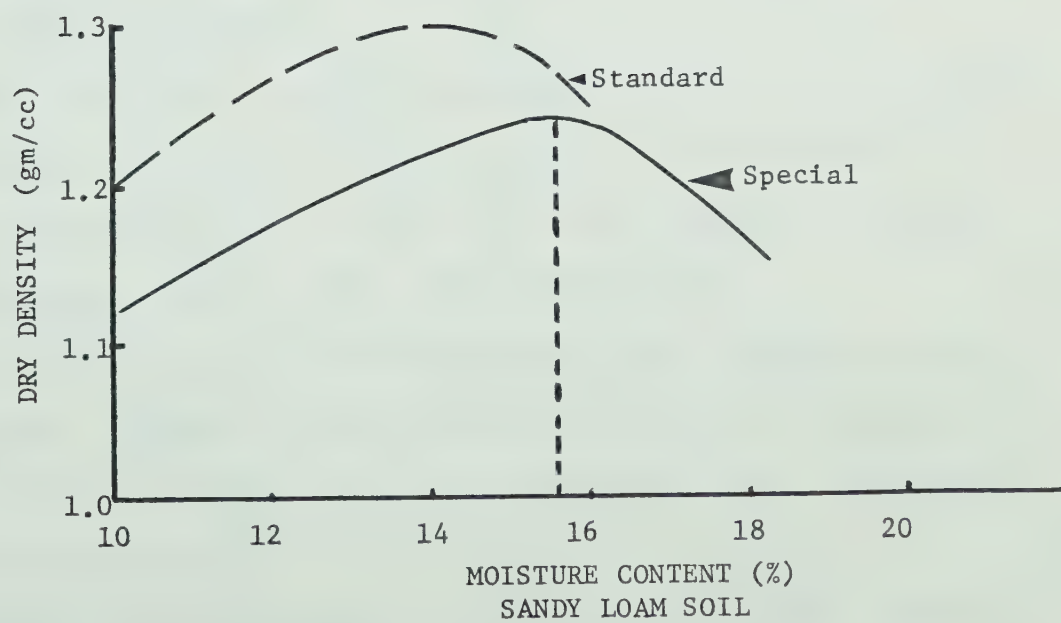
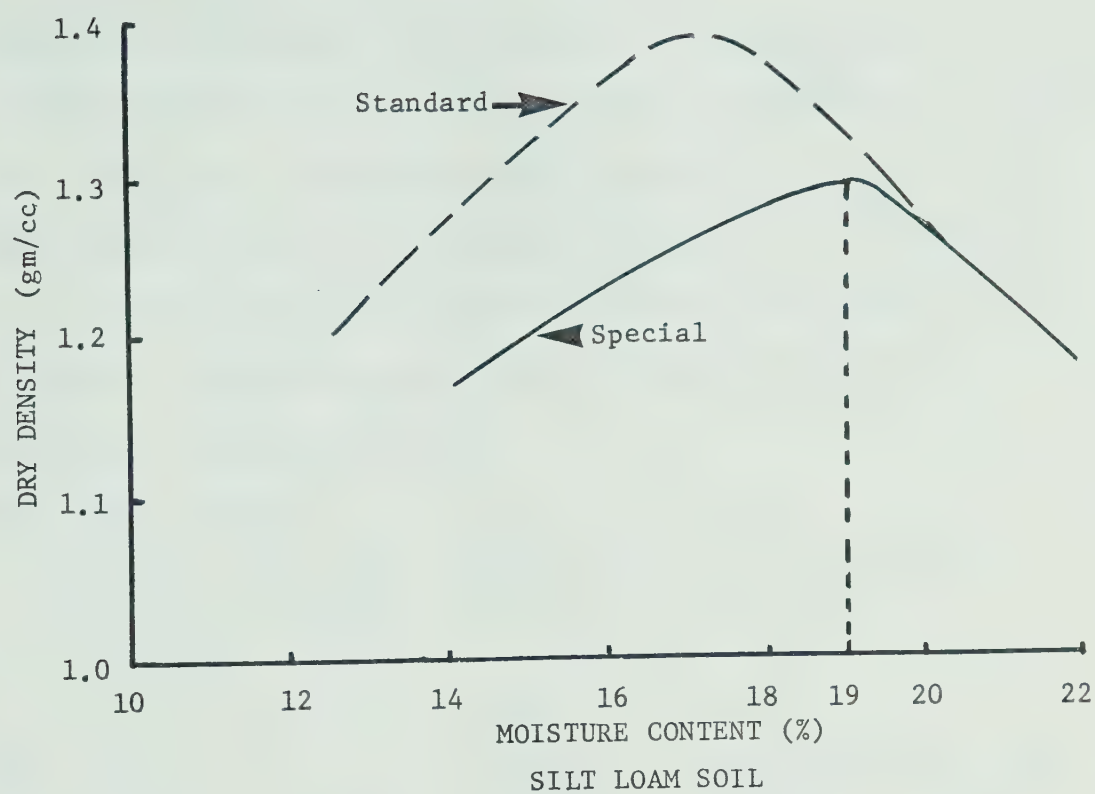


Figure 10: Moisture Content - Dry Density Relationships.

obtained with the special test for the two soils.

Due to the limited size of the vibrator, the maximum depth of the soil, or lift thickness, that could be adequately compacted was 6.4 cm (2 1/2 in). The other lift thickness was one-half of this or 3.2 cm. In order to compact below the seed depth two lifts of 6.4 cm and four lifts of 3.2 cm were used in the experimental work. The number of vibrator passes chosen were two and four as these were considered adequate for the low soil cart speed.

4.2 Experimental Design

The following is the summary of the factors and their levels chosen for the study;

Factor	Code	Level	
Soil type	S	Sandy loam, silt loam	
Moisture content	M	16%	20%
Lift thickness	T	3.2 cm	6.4 cm
Number of vibrator passes	P	2, 4	

The factors soil type and moisture content could not be randomized because of the difficulty in manipulating the moisture content and transferring the soil in and out of the cart. Therefore, a nested factorial design was used (53). The treatments were randomized and repeated three times within a soil type and moisture combination. Treatment in this context is defined as a combination of a level of lift thickness and a level of vibrator pass. The repeats were called blocks (B).

Not all of the soil within the soil cart was sampled. Figure 11 indicates the sampled soil and an illustration of the sampling positions. The positions are identified by the horizontal planes or layers (L).

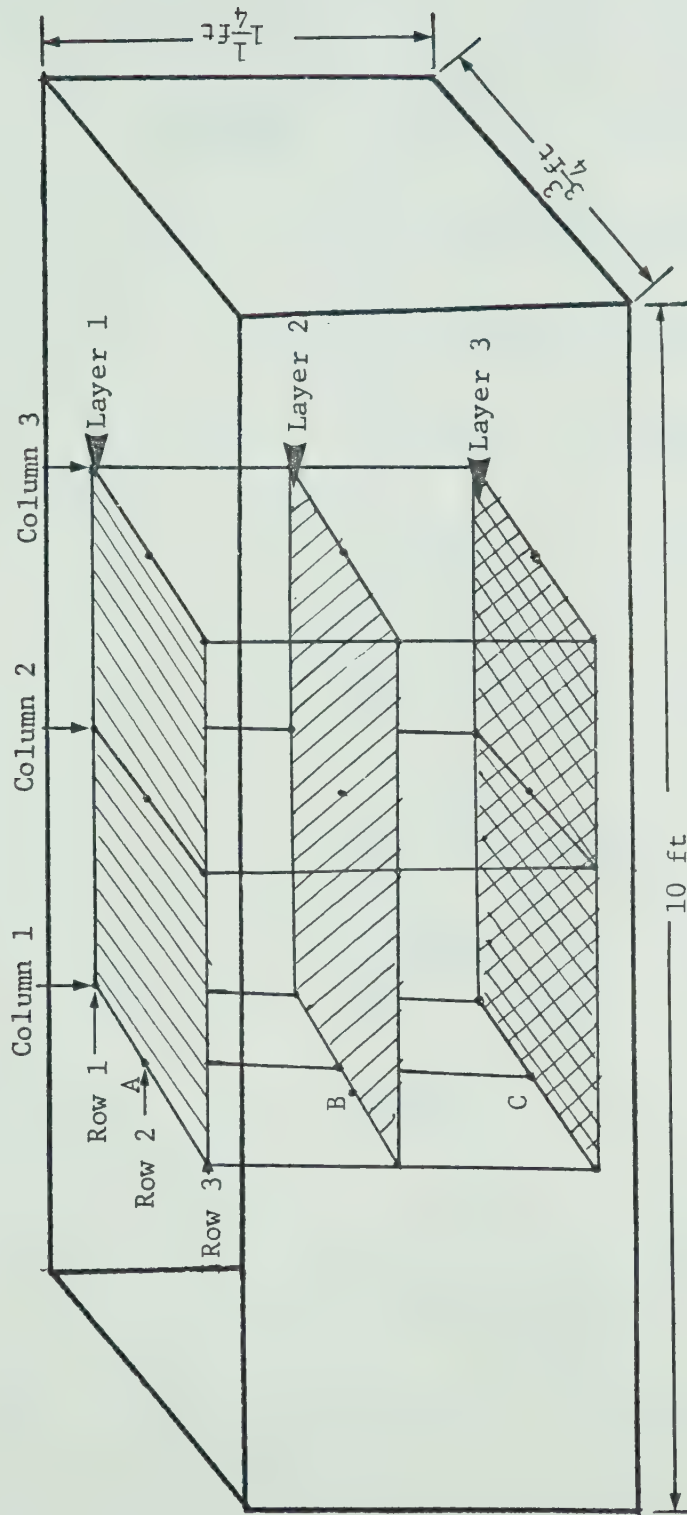


Figure 11: Sampled soil volume or Block with the soil cart.

and vertical planes of rows (R) and columns (C).

The additive model for any observation is:

$$\begin{aligned}
 Y_{ijklmnop} = & \mu + S_i + M_j + SM_{ij} + B_{k(ij)} + \\
 & T_l + TS_{il} + TM_{jl} + TB_{lk(ij)} + P_m + \\
 & PS_{im} + PM_{jm} + PB_{mk(ij)} + PT_{lm} + \\
 & PTB_{mlk(ij)} + L_n + LS_{in} + LM_{jn} + \\
 & LB_{nk(ij)} + LT_{ln} + LTB_{nlk(ij)} + LP_{nm} \\
 & LPB_{nmk(ij)} + R_o + RS_{io} + RM_{jo} + \\
 & RB_{ok(ij)} + RT_{lo} + RTB_{olk(ij)} + RP_{om} + \\
 & RPB_{omk(ij)} + RL_{on} + RLB_{onk(ij)} + C_p \\
 & CS_{ip} + CM_{jp} + CB_{pk(ij)} + CT_{lp} + \\
 & CTB_{plk(ij)} + CP_{mp} + CPB_{pmk(ij)} + CL_{pn} \\
 & CLB_{pnk(ij)} + CR_{po} + CRB_{pok(ij)} + \\
 & \epsilon_{ijklmnop}
 \end{aligned}$$

where:

μ = population mean,

ϵ = experimental error,

$i = 1, 2$

$j = 1, 2$

$k = 1, 2, 3$

$l = 1, 2$

$m = 1, 2$

$$n = 1,2,3$$

$$o = 1,2,3$$

$$p = 1,2,3$$

Values of the expected mean squares are given in table 2. A mixed effects model (i.e. S,M,T,P,L,R and C were fixed at definite levels and B was random) was used and the null hypothesis was tested by the respective error terms.

4.3 Experimental Procedure

4.3.1 Soil Preparation

The soils taken from the field were sieved with a number 4 mesh screen (4.76 mm) to remove stones, coarse root material and some of the larger aggregates. The soil cart was filled with the loose soil to a height of about 30 cm. The moisture content and the density of a soil were determined. Knowing the dry density of the soil and the volume of the cart, the weight of the soil was calculated.

The amount of water required to increase the moisture content of the soil in the cart to the required level of 16% or 20% was calculated. The required amount was added to the soil in two approximately equal applications. After the first application of water, the soil was left covered for about 8 hours with a plastic sheet to prevent evaporation. The soil was tilled, then left for another 8 hour period after the second application of water. The moisture content was determined and when found necessary, more water was added or the soil was left uncovered to let the excess evaporate.

4.3.2 Sample Run

For each treatment the following procedure was used:

1. The moisture content of the soil was determined.
2. The soil was tilled three times to bring the soil to a minimum initial density.
3. The vibrator was lowered to a height of about 10 cm above the floor of the soil cart or about 20 cm below the soil surface.
4. The vibrator was activated and the soil cart was put in motion.
5. At the end of the pass, the vibrator was raised and the soil cart was returned to its original position.
6. Steps 3 to 5 were repeated^{*}.
7. The vibrator was then lowered to the prescribed depth, depending on the lift thickness and steps 4 and 5 were repeated for the number of vibrator passes prescribed.
8. From the accelerometer signal, the frequency and the mean velocity of vibration were determined and recorded.
9. Steps 7 and 8 were repeated until the treatment was complete.
10. The soil density was determined at 27 positions, nine in each of three horizontal layers (figure 11) using the following procedure;
 - (i) The density sampler of known weight was pressed into the soil at position A (see figure 11) to a depth of 4.2 cm (height of the sampler).

* Steps 3 to 6 provided a soil base in the cart similar to a field condition.

- (ii) The sampler and soil was removed and any excess soil struck off. The sampler and soil was weighed and the weight recorded.
- (iii) For position B (10 cm to the near side of A), a new surface was exposed by removing 4.2 cm of soil above it. The density sampler was pressed into the soil and the sampler was removed as before. Then step (ii) was repeated.
- (iv) The steps (i) to (iii) were repeated for position C, in this case soil was removed to a depth of 8.4 cm.
- (v) Similarly, the density was determined for the 24 remaining positions.
- (vi) For each treatment 5 to 6 density samples were oven dried to determine the moisture content of the soil.

For each treatment the soil was brought to a minimum initial density using the rotory tiller so that the treatment would not be biased by the prior treatment. The soil base was left undisturbed as its elastic properties were not expected to change significantly during the experiment.

In a preliminary study, the mean amplitudes of vibration were determined at different air-hammer pressures. Because the mean amplitude was maximum at 50 psi air pressure, it was used throughout the experimental work.

The density was sampled at the twenty seven positions to determine its variations in the three planes and the presence of any gradient. Point B (figure 11), for the density measurement was chosen to be 10 cm to the near side of point A because it was not possible to determine the

density at a point 4.2 cm directly below the point A.

4.4 Data Processing

The amplitude of the vibration can be determined from the signal of the accelerometer by integration;

$$Y = \int \int \ddot{y} dt.$$

As the amplitude or acceleration was not expected to be constant, more than one cycle was required. Since the mean acceleration for one or more cycles is zero, its root mean square must be determined. This was accomplished in the analog computer by limiting the signal to positive values in one case and negative in another. The latter was inverted and then added to the positive values. The root mean square was then integrated while compacting. The integration time period was five seconds, the approximate time for the soil between columns one and three to pass the vibrator.

Assuming the motion of the compactor frame was simple harmonic;

$$Y = A \sin \omega t \dots \dots \dots (1)$$

where,

Y = Displacement at time t in inches

t = Time in seconds

A = Amplitude in inches

$\omega = 2\pi n$ = Angular velocity, in radians/second

n = Frequency in cycles/second.

Second derivative of equation (1) with respect to t ,

$$\ddot{Y} = -A\omega^2 \sin \omega t$$

or $\ddot{Y} = -\omega^2 Y$

or $Y = \frac{\ddot{Y}}{-\omega^2} = -\frac{\ddot{Y}}{(2\pi n)^2} \dots \dots \dots (2)$

$$\ddot{Y}_m = \int_{t_o}^{t_1} \ddot{Y} dt / \int_{t_o}^{t_1} dt$$

$$n_m = \int_{t_o}^{t_1} n dt / \int_{t_o}^{t_1} dt$$

where $\ddot{Y}_m$ = mean acceleration

n_m = mean frequency

Y_m = mean displacement.

Substituting values of $\ddot{Y}_m$ and n_m in equation (2) for $\ddot{Y}$ and n

$$\text{Mean amplitude (Ym) in ft} = \frac{\int_{t_o}^{t_1} \ddot{Y} dt \times \int_{t_o}^{t_1} dt}{(2\pi \int_{t_o}^{t_1} n dt)^2}$$

Chapter 5

RESULTS AND DISCUSSION

The dry densities or densities obtained for the experimental work are given in Appendix I. Mean values of the densities were calculated to indicate the effect of soil type, moisture content, lift thickness and number of vibrator passes. These are given in table 1. In addition, mean densities were calculated (also given in table 1) to determine if density gradients occurred in the three planes of the soil block (figure 11). The differences in the means for layers would indicate the presence of a gradient with respect to depth. Similarly, the means for rows and columns would indicate a gradient across (lateral) and along (longitudinal) the soil block.

5.1 Analysis of Variance

The analysis of the data consisted of using the techniques of analysis of variance and multiple regression. The former technique was used to determine which, if any, of the factors or interactions (see table 2) had a significant effect on the density. Calculations involved in the analysis of variance were made using a library program (17) supplied by the University of Alberta Computing Services. The second and higher order interactions are not included in table 2 because of their limited practical use.

5.1.1 Main Effects

The computed F-values (table 2) indicate that the main effects due to soil type, moisture content, lift thickness and number of passes were highly significant*. This is supported by the observations

* Highly significant and significant implies significance at 0.01 and 0.05 probability levels respectively.

TABLE 1: DRY DENSITY OR DENSITY MEANS.

	<u>Level</u>	<u>Dry Density (gm/cc)</u>
Means for soils	silt loam	0.96
	sandy loam	0.89
Means for moisture contents	20%	0.90
	16%	0.94
Means for lift thickness	6.4 cm	0.91
	3.2 cm	0.93
Means for number of passes	2 passes	0.91
	4 passes	0.93
Means for layers	Layer 1	0.92
	Layer 2	0.92
	Layer 3	0.94
Means for rows	Row 1	0.92
	Row 2	0.93
	Row 3	0.92
Means for columns	Column 1	0.93
	Column 2	0.92
	Column 3	0.93
Grand mean = 0.923 gm/cc		

TABLE 2: ANALYSIS OF VARIANCE (DRY DENSITY OR DENSITY).

Source of Variation	Degrees of Freedom	Expected Mean Squares [†] (mixed model)	Mean Squares	F-value
S	1	$\delta e^2 + 108\delta_B^2 + 648\delta_S^2$	1.276	312.20**
M	1	$\delta e^2 + 108\delta_B^2 + 648\delta_M^2$	0.598	146.31**
SM	1	$\delta e^2 + 108\delta_B^2 + 324\delta_M^2$	0.346	84.83**
B/SM ^{††}	8	$\delta e^2 + 108\delta_B^2$	0.004	
T	1	$\delta e^2 + 54\delta_{TB}^2 + 648\delta_T^2$	0.158	52.42**
TS	1	$\delta e^2 + 54\delta_{TB}^2 + 324\delta_{TS}^2$	0.0033	1.09
TM	1	$\delta e^2 + 54\delta_{TB}^2 + 324\delta_{TM}^2$	0.00019	<1
TB/SM	8	$\delta e^2 + 54\delta_{TB}^2$	0.0030	
P	1	$\delta e^2 + 54\delta_{PB}^2 + 648\delta_P^2$	0.158	106.60**
PS	1	$\delta e^2 + 54\delta_{PB}^2 + 324\delta_{PS}^2$	0.0094	6.34*
PM	1	$\delta e^2 + 54\delta_{PB}^2 + 324\delta_{PM}^2$	0.00014	<1
PB/SM	8	$\delta e^2 + 54\delta_{PB}^2$	0.0014	

Continued

TABLE 2: Continued

Source of Variation	Degrees of Freedom	Expected Mean Squares [†] (mixed model)	Mean Squares	F-values
PT	1	$\delta e^2 + 27\delta_{PTB}^2 + 324\delta_{PT}^2$	0.0025	<1
PTB/SM	8	$\delta e^2 + 27\delta_{PTB}^2$	0.0032	
L	2	$\delta e^2 + 36\delta_{LB}^2 + 432\delta_L^2$	0.0487	40.29**
LS	2	$\delta e^2 + 36\delta_{LB}^2 + 216\delta_{LS}^2$	0.0595	49.20**
LM	2	$\delta e^2 + 36\delta_{LB}^2 + 216\delta_{LM}^2$	0.0075	6.2*
LB/SM	16	$\delta e^2 + 36\delta_{LB}^2$	0.00121	
LT	2	$\delta e^2 + 18\delta_{LTB}^2 + 216\delta_{LT}^2$	0.0070	11.79**
LTB/SM	16	$\delta e^2 + 18\delta_{LTB}^2$	0.0006	
LP	2	$\delta e^2 + 18\delta_{LPB}^2 + 216\delta_{LP}^2$	0.0091	14.66**
LPB/SM	16	$\delta e^2 + 18\delta_{LPB}^2$	0.00062	
R	2	$\delta e^2 + 36\delta_{RB}^2 + 432\delta_R^2$	0.0010	7.26**
RS	2	$\delta e^2 + 36\delta_{RB}^2 + 216\delta_{RS}^2$	0.0018	13.20**

Continued

TABLE 2: Continued

Source of Variation	Degrees of Freedom	Expected Mean Squares [†] (mixed model)	Mean Squares	F-values
RM	2	$\delta e^2 + 36\delta_{RB}^2 + 216\delta_{RM}^2$	0.000021	<1
RB/SM	16	$\delta e^2 + 36\delta_{RB}^2$	0.00014	
RT	2	$\delta e^2 + 18\delta_{RTB}^2 + 216\delta_{RT}^2$	0.00026	2.63
RTB/SM	16	$\delta e^2 + 18\delta_{RTB}^2$	0.00010	
RP	2	$\delta e^2 + 18\delta_{RPB}^2 + 216\delta_{RP}^2$	0.000042	<1
RPB/SM	16	$\delta e^2 + 18\delta_{RPB}^2$	0.00012	
RL	4	$\delta e^2 + 12\delta_{RLB}^2 + 144\delta_{RL}^2$	0.00011	<1
RLB/SM	32	$\delta e^2 + 12\delta_{RLB}^2$	0.00014	
C	2	$\delta e^2 + 36\delta_{CB}^2 + 432\delta_C^2$	0.0068	10.83**
CS	2	$\delta e^2 + 36\delta_{CB}^2 + 216\delta_{CS}^2$	0.0010	1.64

Continued

TABLE 2: Continued

Source of Variation	Degrees of Freedom	Expected Mean Squares [†] (mixed models)	Mean Squares	F-values
CM	2	$\delta e^2 + 36\delta_{CB}^2 + 216\delta_{CM}^2$	0.000125	<1
CB/SM	16	$\delta e^2 + 36\delta_{CB}^2$	0.00063	
CT	2	$\delta e^2 + 18\delta_{CTB}^2 + 216\delta_{CT}^2$	0.0006	2.24
CTB/SM	16	$\delta e^2 + 18\delta_{CTB}^2$	0.00026	
CP	2	$\delta e^2 + 18\delta_{CPB}^2 + 216\delta_{CP}^2$	0.00052	3.47
CPB/SM	16	$\delta e^2 + 18\delta_{CPB}^2$	0.00015	
CL	4	$\delta e^2 + 12\delta_{CLB}^2 + 144\delta_{CL}^2$	0.0011	7.15**
CLB/SM	32	$\delta e^2 + 12\delta_{CLB}^2$	0.00015	
Continued				

TABLE 2: Continued

Source of Variation	Degrees of Freedom	Expected Mean Squares [†] (mixed models)	Mean Squares	F-values
CR	4	$\delta e^2 + 12\delta_{CRB}^2 + 144\delta_{CR}^2$	0.00011	1.42
CRB/SM	32	$\delta e^2 + 12\delta_{CRB}^2$	0.00008	

† Second and higher order interactions are not included.

†† Blocks within soil-moisture combination.

* Significant at .05 probability level.

** Significant at .01 probability level.

of Lewis (33) noted in the literature review.

In more detail, the densities obtained with the silt loam soil were higher than those obtained with the sandy loam soil (table 1). Lewis (33) asserts that more compactive effort is required to achieve equal densities for a cohesive soil. Stating this comment for equal compactive efforts, higher densities will be obtained for a cohesionless soil than for a cohesive soil. The converse relationship, however, was obtained in the experimental work as the sandy loam soil was less cohesive than the silt loam. This converse relationship is largely attributed to the differences in the optimum moisture contents (see figure 10) for the two soils. For the sandy loam soil, the two moisture contents used in the experiment were above the optimum for that soil, whereas the two moisture contents for the silt loam soil bracketed the optimum; that is, the mean densities achieved for the sandy loam soil should be lower than that achieved for the silt loam. The sandy loam soil had a higher organic matter content (4.8%) (see Appendix IV) than the silt loam soil (4.1%) and no doubt this also contributed to the densities obtained in the experiment.

The density for the 3.2 cm lift thickness was higher than that obtained for the 6.4 cm thickness. Though the same amount of compactive effort or energy was expended for both the lift thicknesses, the energy per unit volume of the soil received by 3.2 cm lift thickness was greater, thus compacting it more. The compactive energy can also account for the greater density obtained for the four passes; that is, the energy expended was more with four vibrator passes than with two.

The computed F-values (table 2) also indicate that there were highly

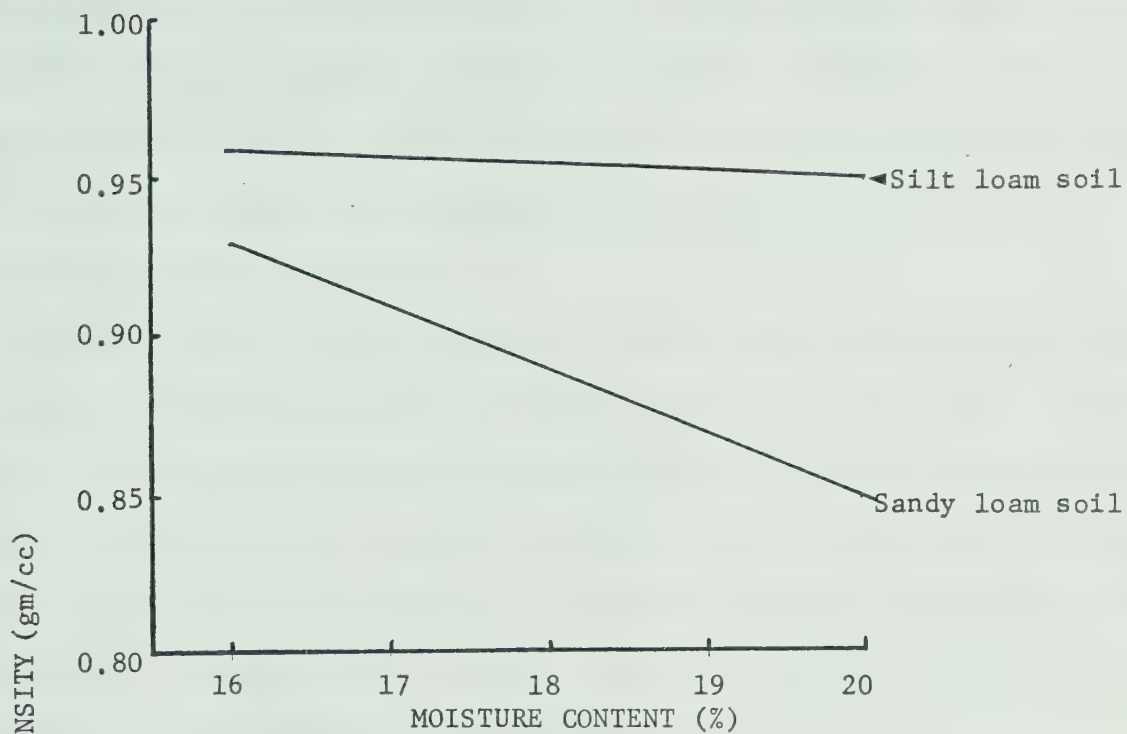


Figure 12a: Soil-Moisture Interaction.

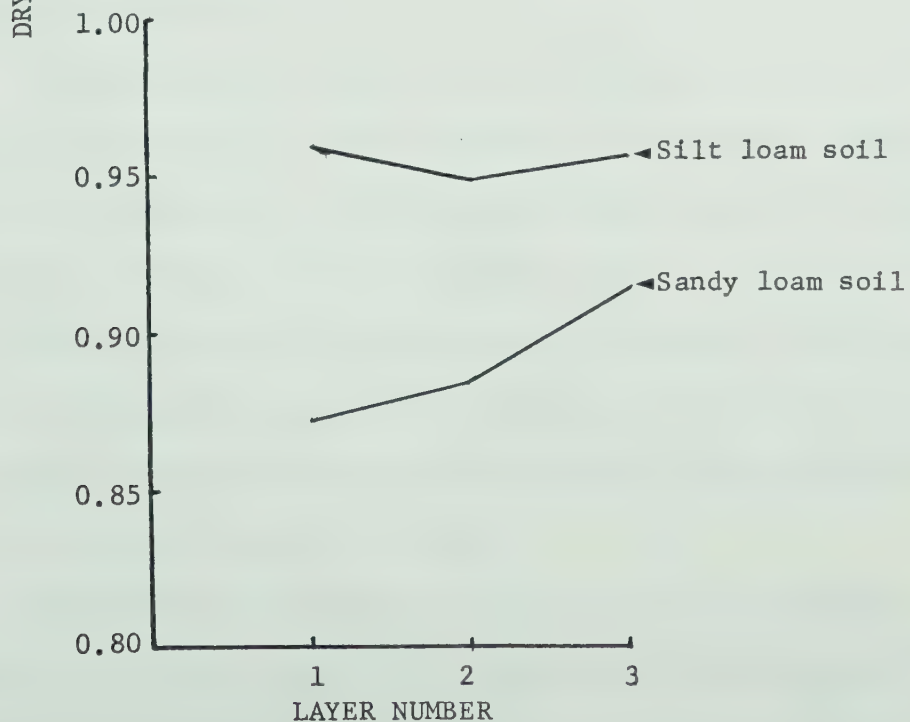


Figure 12b: Soil-Layer Interaction.

significant differences in densities among the layers, rows and columns. The Duncan's new multiple range test (44) (.05 probability level) was carried out on these density means. The test indicates that the mean densities for layers one and two are not different, whereas the mean density of layer three is different from the first two. The greater mean density for layer three is attributed to the cumulative effect of compacting the other two layers.

Duncan's test for rows shows that the mean densities for row one and three are not different but for row two is different. The greater density for row two indicates an 'edge or boundary effect'. At the edges, the soil moves laterally as well as vertically and in so doing the gain in density is not as great as at the center. The 'boundary effect' is similar to what Harrison (24) obtained with a roller. There is no apparent reason for the gradients in the longitudinal plane (column).

5.1.2 Interactions

The interaction (table 2) of soil-moisture content (S x M) indicates that the density of the soil depends on the moisture content (see figure 12a). The densities of the two soils were similar at the lower moisture content of 16% but at the 20% moisture content, the density of sandy loam soil was considerably less than the silt loam soil. The reason suggested for the differential response is optimum moisture content. The optimum moisture (density) for the sandy loam soil (15.6%) was considerably less than for the silt loam soil (19%).

The differential response indicated by the interaction of soil-layer (S x L), see figure 12b, suggests that the cumulative effect of the compactive effort on layers depends on the soil type. For the silt loam, there was little or no cumulative effect because of the slightly cohesive

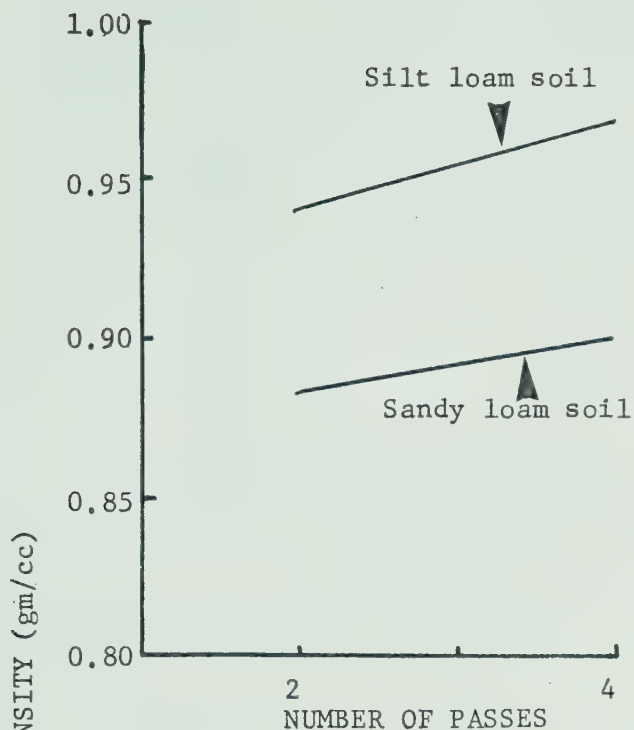


Figure 13a: Soil-Pass Interaction.

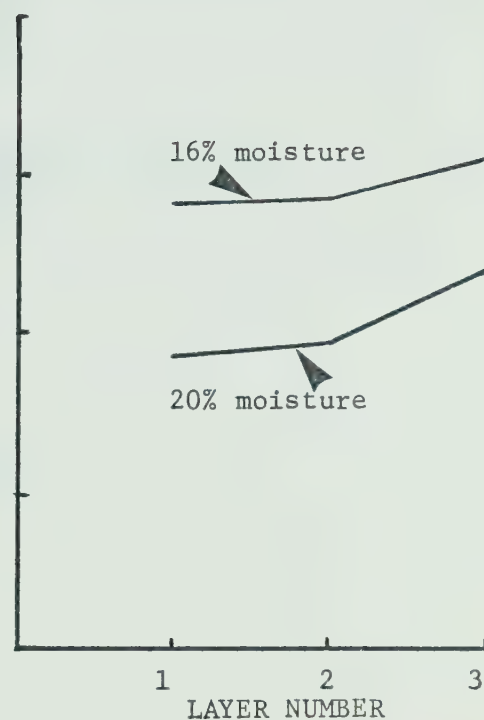


Figure 13b: Moisture-Layer Interaction.

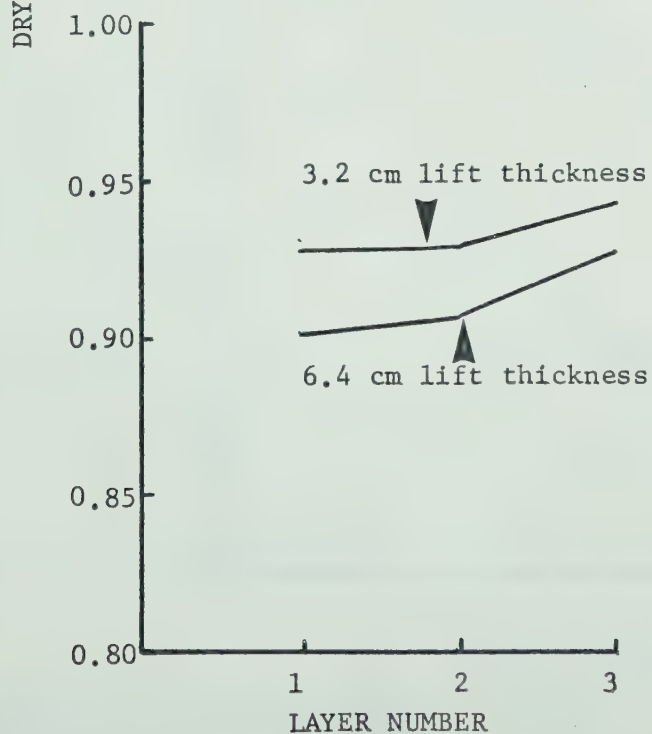


Figure 13c: Layer-Lift Thickness Interaction.

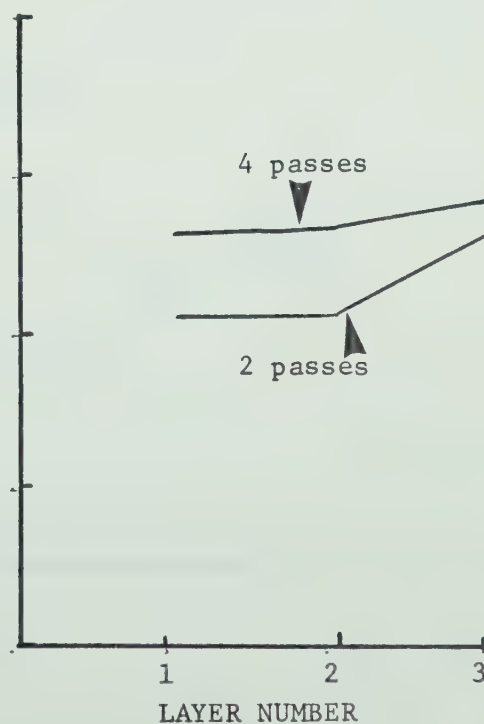


Figure 13d: Layer-Pass Interaction.

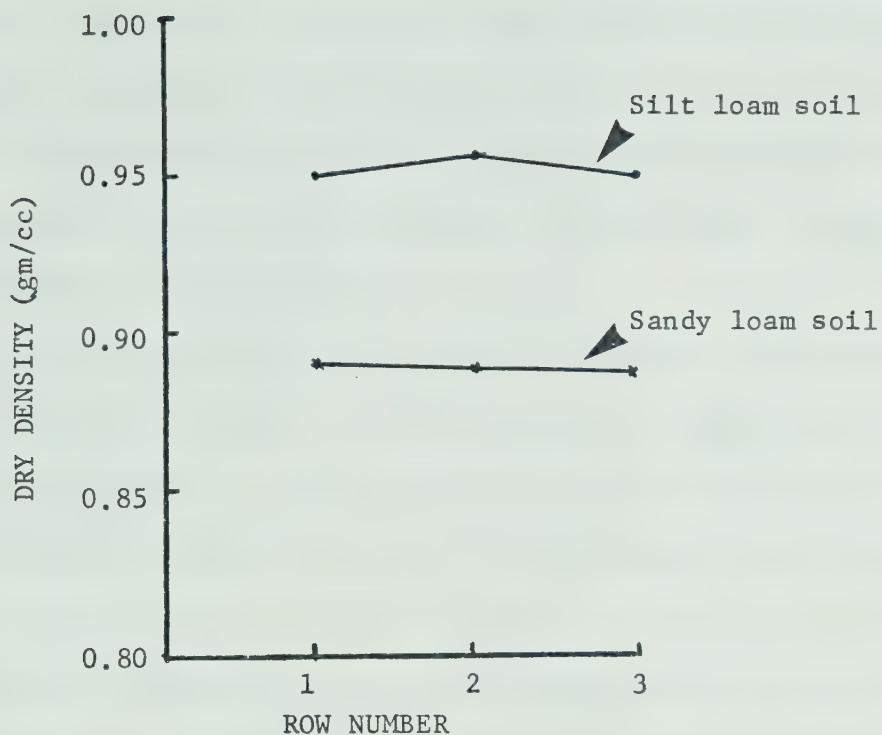


Figure 14a: Soil-Row Interaction.

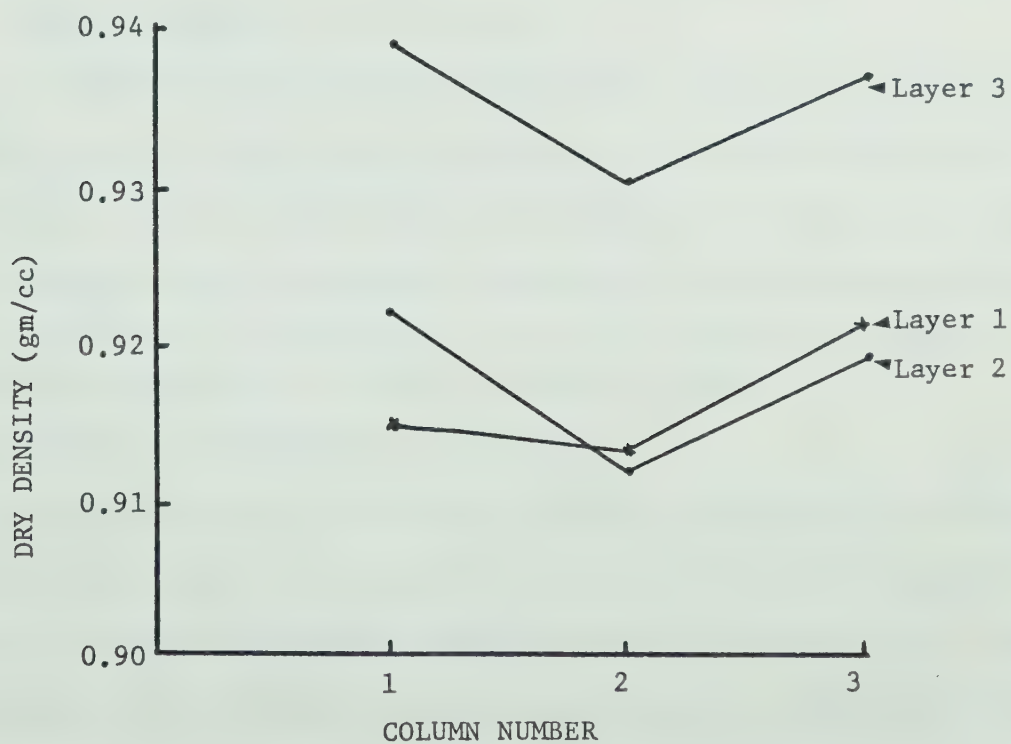


Figure 14b: Layer-Column Interaction.

nature of the soil. As already noted (33) cohesive soils require higher compactive efforts than cohesionless soils. It would appear that the compactive efforts for compacting the subsequent and final lifts were not adequate to increase the densities in layers two and three for the silt loam soil.

The interactions of the number of passes - soil type ($P \times S$), layer-moisture content ($L \times M$), layer-lift thickness ($L \times T$), layer-number of passes ($L \times P$), soil type-row ($S \times R$) and layer-column ($L \times C$) are shown in figure 13 and 14. The converging trend at layer three for the interactions of $L \times M$, $L \times T$ and $L \times P$ may be due to the cumulative effect of compacting the other two layers; that is, the main effects of moisture, lift thickness and number of vibrator passes may diminish with increased density.

5.2 Density Variation Within Layers

It has been pointed out by Scheffe (41) that the natural logarithms of the variances are normally distributed. Therefore the analysis of variance for natural logarithms of variances (of densities for each layer) was carried out and it was found that none of the factors and interactions were statistically significant; that is, the density variations within the layers were the same for all the layers.

5.3 Frequency and Amplitude of Vibration

The frequency and amplitude of vibration along with the density obtained are given in Appendix II. As can be seen, the frequency was higher for the sandy loam soil than it was for the silt loam. Though the vibration of the vibrator was forced, the frequency could vary through a limited range. The change in frequency would likely be in the direction of the state of resonance. As noted previously (47), the frequency at the

TABLE 3: ANALYSIS OF VARIANCE FOR THE REGRESSION.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F-value
Attributed to regression	2	0.02996	0.01498	119.260**
Deviation from regression	13	0.00163	0.00012	
Total	15	0.03159		

Regression equation;

$$Y_D = 0.68576 + 14.51242X_A - 170.07381X_A^2$$

Coefficient of determination (R^2) = 0.948.

Standard error of estimate = 0.0011 gm/cc.

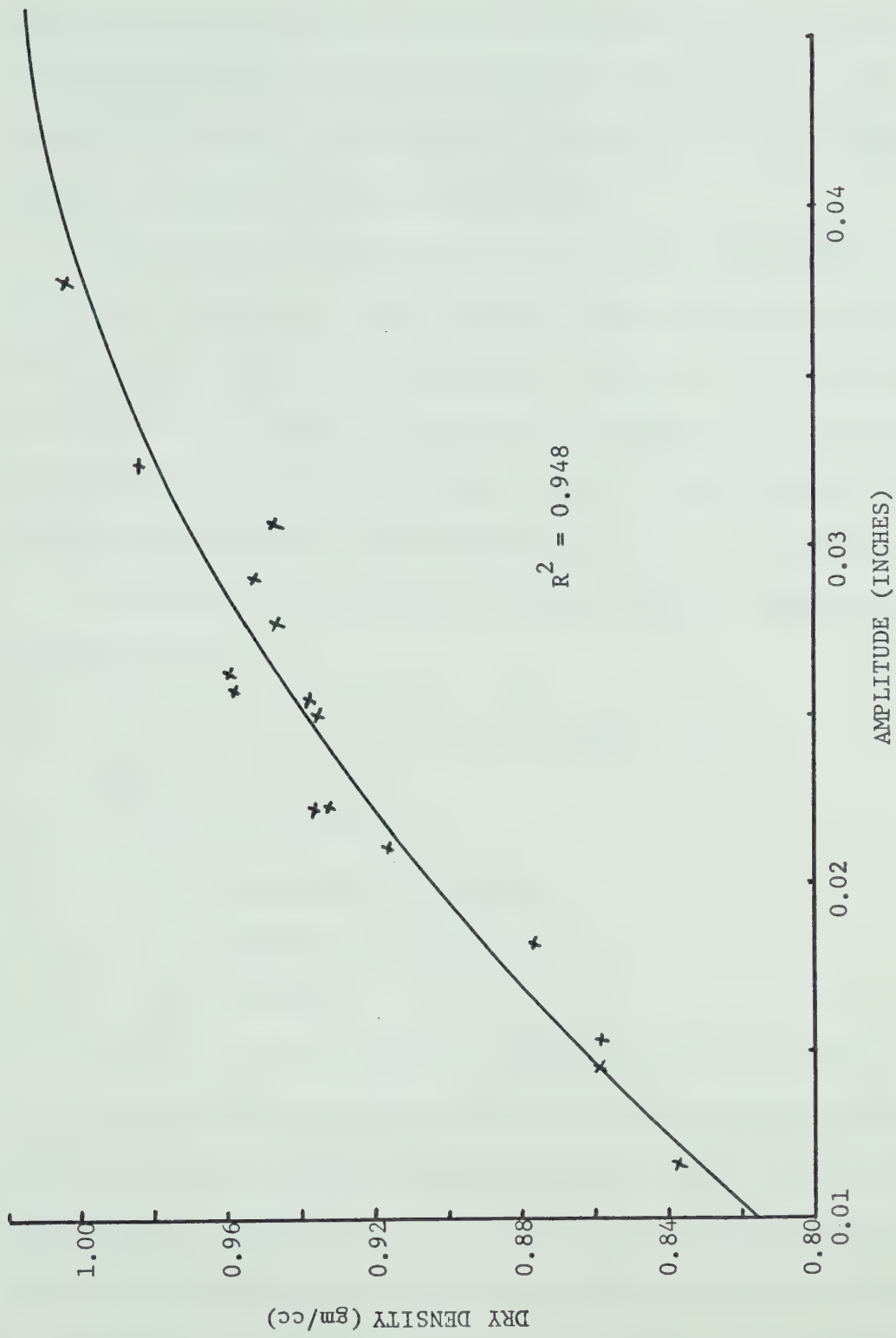


Figure 15: Dry Density-Amplitude relationship.

state of resonance is approximately equal to the natural frequency of the vibrator and the vibrating portion of the supporting soil. In other words, the frequency was not only a function of the air pressure used to operate the hammer but the soil as well.

The amplitude of vibration is treated as an independent variable but it is also a function of the density. The multiple regression technique was employed to arrive at a prediction equation for the density in terms of the other two variables, frequency and amplitude. Calculations for multiple regression were performed using a stepwise multiple regression program (22) supplied by the University of Alberta Computing Services.

The general model considered for the multiple regression had the following form;

$$Y_D = A_0 + A_1 X_F + A_2 X_F^2 + A_3 X_A + A_4 A^2$$

where

Y_D = Dry density,

X_F = Frequency of vibration,

X_A = Amplitude of vibration,

A_0 = constant,

$A_1, \dots, A_4$ = multiple partial regression coefficients.

It was desirable to keep the regression equation as simple as possible, thus a computer program (22) for stepwise multiple regression, limiting the exponents of X_F and X_A , was used to determine the relationship. The independent variables given in the general model were made available to the program. The regression and the results of the regression analysis are given in table 3. As can be seen, only the amplitude squared entered into the regression. The squared multiple correlation coefficient or coefficient of determination (R^2) is 0.948 indicating that 94.8% of the

variation in the density is due to the amplitude and therefore, a relationship between the two variables exists.

The frequency did not reduce the sum of squares and though this would suggest that the density was independent of the frequency, the frequency range in the experimental work was only 37-41 cycles per sec. This narrow frequency range falls within the range of 36-40 cycles per sec for which Lewis (33) suggests that there is no appreciable change in the density with a change in the frequency of vibration.

The nature of the regression equation between the density and the amplitude is parabolic (figure 15) suggesting that at some amplitude (not included in the experimental work) a further increase would not increase the density.

5.4 Summary

The density obtained with the experimental vibrator increased with the depth due to the cumulative effect of the compactive effort. However, the effect was not significant on the silt loam soil. It is evident from table 1 that it is feasible to obtain any density gradient.

Although the density variations within the layers were similar, there was a 'boundary effect' in the compacted soil block. In laboratory tillage studies, the 'boundary effect' can be minimized using an experimental design, such as confounding block design (53) which eliminates the block differences from the experimental error or use only one pass of the tillage tool for each soil preparation. In field work, the 'boundary effect' can be minimized by using some overlap.

The experimental vibrator indicated the feasibility of compacting the soil without soil removal. This would save labour and time in the case of laboratory tillage studies and is the only practical way for field

compaction. The ability to compact the soil to a desired density gradient by selecting different lift thicknesses and vibrator passes is also of considerable merit either for laboratory tillage or as a practical field machine. There is also the advantage that the compactive energy can be transmitted to the compaction device other than through the tractor drive wheels, an advantage noted by Harrison (24) with respect to vibratory tillage.

The regression equation given in table 3 can only be used in describing the experimental density data in terms of amplitude of vibration. Although 94% of the variation in the density (Y) is explained by the amplitude (X), the practical use of the equation is limited because the frequency range was limited.

Chapter 6

SUMMARY AND CONCLUSIONS

Luth and Wismer (34) developed a vibratory compactor which would produce various density gradients with respect to depth in air dry sand. For example, they were able to obtain a gradient, in which the density increased with depth, without required soil removal when using a roller. The experimental work indicates that this is also feasible for typical agricultural soils except that the soil above the compacting plate has to be aided in its transfer over the compacting plate.

Vibratory compaction has two possible applications; for laboratory tillage studies and in the cultural practice of seed-bed preparation. With the experimental vibrator, the densities obtained were low. In seed-bed preparation, the vibrator could compact the soil around and below the seed and, for that purpose, the order of densities obtained is adequate (14).

Soil densities obtained with the vibrator were dependent on the soil type, moisture content, thickness of soil layer and the number of vibrator passes. Higher densities can be obtained if the soils are compacted at their optimum moisture contents as indicated by a significant soil-moisture interaction.

There was a density gradient symmetrical with the centre of the sampled soil block (boundary effect) which would necessitate a confounding block design (53) for tillage studies. For field use, some overlap might be required. The density variations within the layers were similar in all the layers.

The cumulative effect of the compactive effort was present in the

sandy loam soil but was absent in the case of the silt loam soil. This differential response would have to be considered to secure similar densities and profiles for different soil types.

The narrow range of the frequency in the experiment limits the practical value of the prediction equation. As for the recording penetrometer, it was not useful being insensitive to the density variations obtained with the vibrator.

Chapter 7

RECOMMENDATIONS

On the basis of the information obtained during this investigation some recommendations can be made:

1. A larger pneumatic hammer would achieve greater densities at higher travel rates with fewer passes. It would also increase the frequency and amplitude range, thereby providing more useful prediction equation.
2. Gamma ray equipment for density measurements would be quicker than the procedure used and provide a more accurate density gradient or profile.

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APPENDICES

The following terminology has been used for Appendices I and II.

- S1 - Silt loam soil
- S2 - Sandy loam soil
- M1 - $20 \pm 0.3\%$ moisture content
- M2 - $16 \pm 0.2\%$ moisture content
- T1 - 2 Pass and 6.4 cm Lift Thickness
- T2 - 2 Pass and 3.2 cm Lift Thickness
- T3 - 4 Pass and 6.4 cm Lift Thickness
- T4 - 4 Pass and 3.2 cm Lift Thickness

In Appendix I, repeat means repeat of a treatment within a soil-moisture combination. Also the Rows and Columns in a layer are the same as in the soil block (see figure 11).

APPENDIX I: SOIL DRY DENSITIES.

SILT LOAM SOIL

20 PERCENT MOISTURE

TREATMENT NUMBER 1

LAYER 1

0.92	0.91	0.93
0.94	0.95	0.93
0.94	0.94	0.95

LAYER 2

0.94	0.94	0.94
0.96	0.97	0.95
0.96	0.94	0.95

LAYER 3

0.99	0.96	0.98
0.98	0.99	0.97
0.97	0.96	0.98

16 PERCENT MOISTURE

REPEAT NUMBER 1

0.94	0.96	0.96
0.96	0.94	0.98
0.97	0.93	0.95

0.90	0.90	0.92
0.90	0.91	0.93
0.92	0.90	0.92

0.91	0.91	0.91
0.92	0.92	0.92
0.93	0.91	0.91

TREATMENT NUMBER 1

REPEAT NUMBER 2

LAYER 1

0.92	0.91	0.91
0.90	0.89	0.92
0.89	0.92	0.91

0.93	0.92	0.92
0.93	0.94	0.94
0.94	0.92	0.95

LAYER 2

0.91	0.90	0.90
0.90	0.91	0.92
0.91	0.90	0.88

0.91	0.93	0.93
0.93	0.92	0.93
0.91	0.92	0.93

LAYER 3

0.95	0.93	0.95
0.92	0.95	0.94
0.93	0.92	0.93

0.92	0.92	0.91
0.94	0.94	0.94
0.92	0.93	0.94

SILT LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 1

REPEAT NUMBER 3

LAYER 1

0.90	0.90	0.92	0.94	0.92	0.93
0.92	0.93	0.94	0.96	0.94	0.96
0.90	0.91	0.93	0.95	0.93	0.92

LAYER 2

0.89	0.91	0.92	0.92	0.93	0.94
0.91	0.91	0.91	0.95	0.95	0.94
0.91	0.91	0.92	0.96	0.95	0.93

LAYER 3

0.91	0.91	0.93	1.01	0.99	1.00
0.93	0.92	0.92	1.01	0.99	0.98
0.92	0.92	0.93	0.98	0.98	1.01

TREATMENT NUMBER 2

REPEAT NUMBER 1

LAYER 1

0.92	0.95	0.93	0.98	0.98	0.98
0.93	0.94	0.95	1.00	0.98	0.99
0.91	0.95	0.95	0.96	0.97	0.98

LAYER 2

0.92	0.92	0.93	0.93	0.94	0.96
0.95	0.93	0.95	0.95	0.95	0.94
0.91	0.91	0.94	0.95	0.97	0.96

LAYER 3

0.94	0.93	0.95	0.97	0.97	0.95
0.95	0.95	0.93	0.97	0.97	0.96
0.95	0.95	0.95	0.97	0.96	0.95

SILT LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 2

REPEAT NUMBER 2

LAYER 1

0.95	0.93	0.92
0.95	0.96	0.93
0.95	0.95	0.93

0.95	0.94	0.97
0.97	0.95	0.97
0.94	0.96	0.97

LAYER 2

0.95	0.93	0.92
0.95	0.93	0.92
0.94	0.94	0.94

0.95	0.93	0.94
0.93	0.94	0.94
0.93	0.95	0.94

LAYER 3

0.94	0.94	0.93
0.97	0.96	0.94
0.96	0.94	0.94

0.95	0.93	0.94
0.94	0.94	0.95
0.93	0.96	0.93

TREATMENT NUMBER 2

REPEAT NUMBER 3

LAYER 1

0.93	0.93	0.97
0.95	0.95	0.96
0.96	0.93	0.96

0.96	0.96	0.98
0.97	0.96	0.98
0.96	0.96	0.97

LAYER 2

0.95	0.93	0.96
0.95	0.93	0.96
0.96	0.94	0.95

0.93	0.95	0.94
0.95	0.94	0.94
0.94	0.94	0.91

LAYER 3

0.95	0.95	0.97
0.97	0.97	0.98
0.97	0.98	0.99

0.95	0.96	0.96
0.96	0.97	0.95
0.93	0.94	0.94

SILT LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 3

REPEAT NUMBER 1

LAYER 1

0.96	0.94	0.94
0.96	0.94	0.96
0.96	0.93	0.96

0.98	0.96	0.95
0.98	0.97	0.96
0.97	0.96	0.95

LAYER 2

0.98	0.96	0.96
0.98	0.97	0.98
0.98	0.95	0.96

0.93	0.94	0.93
0.97	0.96	0.96
0.94	0.94	0.93

LAYER 3

0.97	0.98	0.95
0.98	0.97	0.97
0.96	0.97	0.96

0.95	0.93	0.96
0.94	0.95	0.96
0.96	0.95	0.94

TREATMENT NUMBER 3

REPEAT NUMBER 2

LAYER 1

0.94	0.93	0.95
0.96	0.96	0.95
0.94	0.94	0.94

0.97	0.96	0.97
0.98	0.98	0.98
0.96	0.98	0.99

LAYER 2

0.95	0.96	0.95
0.96	0.95	0.93
0.97	0.95	0.94

0.95	0.96	0.96
0.94	0.95	0.94
0.94	0.95	0.95

LAYER 3

0.94	0.94	0.94
0.96	0.94	0.94
0.95	0.96	0.95

0.93	0.94	0.94
0.95	0.95	0.92
0.93	0.92	0.92

SILT LOAM SOIL

20 PERCENT MOISTURE

TREATMENT NUMBER 3

LAYER 1

0.93	0.92	0.93
0.94	0.95	0.95
0.92	0.93	0.92

LAYER 2

0.94	0.94	0.92
0.93	0.93	0.93
0.92	0.91	0.95

LAYER 3

0.96	0.93	0.97
0.96	0.94	0.95
0.93	0.96	0.98

16 PERCENT MOISTURE

REPEAT NUMBER 3

0.96	0.96	0.97
0.95	0.96	1.00
0.95	0.96	0.99

0.94	0.96	0.95
0.94	0.96	0.96
0.95	0.94	0.93

0.94	0.97	0.93
0.93	0.96	0.97
0.94	0.97	0.97

TREATMENT NUMBER 4

REPEAT NUMBER 1

LAYER 1

0.99	0.99	1.01
0.99	1.01	1.01
0.99	1.00	1.01

1.01	1.01	1.02
1.00	0.99	1.01
0.99	0.99	0.99

LAYER 2

0.99	0.98	1.00
1.01	0.98	0.99
0.98	0.98	1.00

1.01	0.98	1.01
0.99	0.98	1.01
0.98	0.99	1.01

LAYER 3

0.96	0.95	0.97
0.97	0.95	0.97
0.99	0.98	0.99

0.99	0.97	0.99
0.98	0.97	0.98
0.97	0.95	0.98

SILT LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 4

REPEAT NUMBER 2

LAYER 1

0.99	0.96	0.97
0.99	0.99	0.96
1.00	1.00	0.97

0.99	1.01	1.02
1.01	1.02	1.03
1.01	1.03	1.03

LAYER 2

0.99	0.96	0.95
0.98	0.96	0.95
0.98	0.97	0.95

0.96	0.98	0.96
0.99	0.98	1.00
0.97	0.99	0.99

LAYER 3

0.98	0.95	0.95
0.98	0.95	0.95
0.97	0.96	0.95

0.96	0.96	0.96
0.99	0.99	0.99
1.00	0.98	0.97

TREATMENT NUMBER 4

REPEAT NUMBER 3

LAYER 1

1.00	0.98	0.99
0.98	0.98	1.00
0.96	0.98	1.00

1.01	1.00	1.00
1.03	1.00	1.03
0.99	1.00	1.03

LAYER 2

0.98	0.95	0.97
0.97	0.95	0.97
0.97	0.95	0.97

1.01	0.98	1.02
1.02	1.00	1.02
0.99	0.99	1.00

LAYER 3

0.97	0.96	0.98
0.98	0.96	0.98
0.96	0.96	0.99

0.97	0.99	1.02
0.99	0.98	1.00
0.99	1.01	1.02

SANDY LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 1

REPEAT NUMBER 1

LAYER 1

0.80	0.81	0.82
0.80	0.80	0.82
0.82	0.81	0.82

0.89	0.87	0.89
0.86	0.86	0.90
0.86	0.88	0.89

LAYER 2

0.83	0.81	0.84
0.81	0.79	0.83
0.83	0.80	0.81

0.92	0.91	0.92
0.92	0.90	0.90
0.90	0.89	0.90

LAYER 3

0.88	0.88	0.88
0.88	0.88	0.87
0.86	0.86	0.86

0.93	0.93	0.93
0.93	0.92	0.93
0.94	0.93	0.95

TREATMENT NUMBER 1

REPEAT NUMBER 2

LAYER 1

0.80	0.83	0.82
0.79	0.80	0.81
0.79	0.81	0.81

0.91	0.93	0.91
0.90	0.88	0.91
0.90	0.89	0.90

LAYER 2

0.84	0.83	0.84
0.81	0.82	0.84
0.81	0.81	0.80

0.91	0.90	0.92
0.90	0.92	0.92
0.91	0.90	0.92

LAYER 3

0.89	0.88	0.86
0.87	0.86	0.87
0.88	0.85	0.86

0.93	0.93	0.94
0.94	0.95	0.94
0.96	0.97	0.96

SANDY LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 1

REPEAT NUMBER 3

LAYER 1

0.79	0.80	0.81	0.89	0.88	0.89
0.79	0.81	0.81	0.88	0.89	0.89
0.78	0.80	0.80	0.89	0.88	0.89

LAYER 2

0.84	0.82	0.83	0.91	0.91	0.91
0.82	0.82	0.82	0.92	0.90	0.92
0.83	0.81	0.83	0.91	0.91	0.91

LAYER 3

0.88	0.87	0.88	0.93	0.92	0.93
0.90	0.88	0.90	0.92	0.93	0.94
0.89	0.86	0.90	0.93	0.93	0.93

TREATMENT NUMBER 2

REPEAT NUMBER 1

LAYER 1

0.83	0.83	0.85	0.92	0.90	0.92
0.83	0.84	0.83	0.92	0.91	0.95
0.85	0.85	0.84	0.92	0.91	0.93

LAYER 2

0.85	0.84	0.84	0.96	0.92	0.94
0.86	0.84	0.85	0.95	0.93	0.95
0.87	0.85	0.86	0.93	0.93	0.94

LAYER 3

0.89	0.86	0.87	0.97	0.93	0.95
0.89	0.88	0.87	0.97	0.96	0.95
0.90	0.87	0.88	0.95	0.95	0.95

SANDY LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 2

REPEAT NUMBER 2

LAYER 1

0.82	0.82	0.82
0.82	0.83	0.83
0.82	0.83	0.84

0.91	0.90	0.95
0.92	0.92	0.93
0.91	0.91	0.93

LAYER 2

0.84	0.83	0.86
0.84	0.82	0.86
0.85	0.82	0.84

0.93	0.91	0.93
0.95	0.94	0.93
0.94	0.91	0.93

LAYER 3

0.89	0.85	0.88
0.87	0.87	0.89
0.89	0.87	0.89

0.95	0.95	0.95
0.94	0.93	0.95
0.96	0.93	0.95

TREATMENT NUMBER 2

REPEAT NUMBER 3

LAYER 1

0.83	0.83	0.85
0.84	0.83	0.84
0.86	0.85	0.85

0.93	0.91	0.93
0.89	0.93	0.91
0.92	0.92	0.92

LAYER 2

0.87	0.87	0.86
0.85	0.84	0.84
0.85	0.85	0.85

0.93	0.93	0.93
0.93	0.94	0.93
0.92	0.93	0.92

LAYER 3

0.90	0.87	0.89
0.88	0.88	0.89
0.90	0.88	0.90

0.95	0.94	0.96
0.96	0.95	0.95
0.96	0.96	0.95

SANDY LOAM SOIL

20 PERCENT MOISTURE

16 PERCENT MOISTURE

TREATMENT NUMBER 3

REPEAT NUMBER 1

LAYER 1

0.87	0.86	0.86
0.87	0.87	0.87
0.85	0.88	0.86

0.89	0.89	0.92
0.91	0.89	0.92
0.92	0.92	0.92

LAYER 2

0.87	0.85	0.86
0.87	0.86	0.86
0.86	0.85	0.84

0.94	0.93	0.92
0.94	0.95	0.94
0.95	0.93	0.93

LAYER 3

0.89	0.88	0.88
0.89	0.87	0.90
0.89	0.86	0.87

0.96	0.93	0.96
0.95	0.96	0.96
0.97	0.95	0.97

TREATMENT NUMBER 3

REPEAT NUMBER 2

LAYER 1

0.82	0.82	0.84
0.82	0.82	0.83
0.81	0.84	0.84

0.91	0.89	0.91
0.91	0.90	0.90
0.91	0.91	0.91

LAYER 2

0.83	0.83	0.83
0.83	0.81	0.82
0.82	0.80	0.81

0.97	0.94	0.95
0.96	0.93	0.93
0.96	0.94	0.95

LAYER 3

0.89	0.87	0.89
0.88	0.87	0.89
0.87	0.86	0.86

0.96	0.95	0.96
0.95	0.94	0.96
0.94	0.94	0.95

SANDY LOAM SOIL

20 PERCENT MOISTURE

TREATMENT NUMBER 3

LAYER 1

0.82	0.82	0.84
0.82	0.83	0.85
0.81	0.83	0.83

LAYER 2

0.87	0.84	0.86
0.86	0.83	0.85
0.86	0.84	0.83

LAYER 3

0.90	0.87	0.90
0.89	0.87	0.87
0.89	0.87	0.87

16 PERCENT MOISTURE

REPEAT NUMBER 3

0.89	0.90	0.92
0.91	0.91	0.89
0.91	0.90	0.91

0.93	0.93	0.93
0.94	0.93	0.93
0.93	0.94	0.93

0.94	0.93	0.96
0.95	0.94	0.95
0.95	0.94	0.95

TREATMENT NUMBER 4

REPEAT NUMBER 1

LAYER 1

0.87	0.87	0.86
0.88	0.88	0.87
0.88	0.85	0.87

0.94	0.91	0.92
0.93	0.90	0.93
0.93	0.92	0.94

LAYER 2

0.89	0.87	0.89
0.89	0.88	0.90
0.89	0.86	0.88

0.95	0.94	0.94
0.96	0.92	0.94
0.97	0.93	0.94

LAYER 3

0.92	0.89	0.91
0.92	0.89	0.90
0.91	0.89	0.89

0.97	0.95	0.96
0.95	0.93	0.95
0.98	0.95	0.95

SANDY LOAM SOIL

20 PERCENT MOISTURE

TREATMENT NUMBER 4

LAYER 1

0.89	0.87	0.88
0.86	0.87	0.88
0.86	0.87	0.86

LAYER 2

0.88	0.86	0.86
0.85	0.86	0.87
0.87	0.85	0.86

LAYER 3

0.91	0.89	0.89
0.92	0.89	0.90
0.89	0.89	0.89

16 PERCENT MOISTURE

REPEAT NUMBER 2

0.96	0.93	0.93
0.94	0.91	0.92
0.94	0.92	0.93

0.94	0.93	0.93
0.94	0.92	0.93
0.94	0.92	0.93

0.96	0.95	0.95
0.97	0.95	0.94
0.96	0.94	0.96

TREATMENT NUMBER 4

REPEAT NUMBER 3

LAYER 1

0.83	0.82	0.84
0.83	0.83	0.85
0.83	0.83	0.85

0.94	0.93	0.94
0.94	0.93	0.93
0.93	0.94	0.92

LAYER 2

0.84	0.84	0.87
0.86	0.83	0.87
0.87	0.84	0.86

0.96	0.92	0.96
0.96	0.94	0.95
0.94	0.95	0.96

LAYER 3

0.89	0.88	0.88
0.90	0.88	0.88
0.90	0.87	0.89

0.97	0.95	0.97
0.97	0.95	0.97
0.96	0.97	0.96

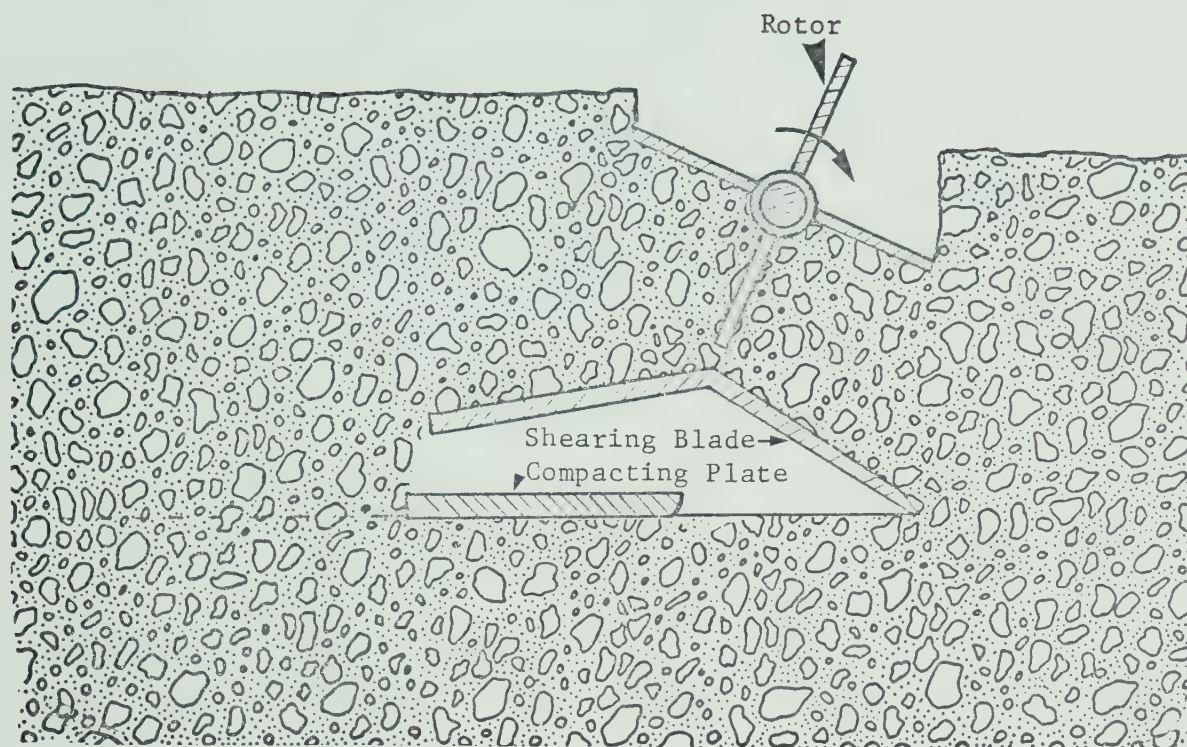
APPENDIX II: EXPERIMENTAL DATA* FOR DENSITY, FREQUENCY AND AMPLITUDE.

S. No.	Designation	Density (Y_D) (gm/cc)	Frequency (X_F) (cps)	Amplitude (X_A) (inches)
1	S1M1T1	0.9285	37.00	0.0212
2	S1M1T2	0.9448	37.45	0.0294
3	S1M1T3	0.9496	37.35	0.0278
4	S1M1T4	0.9767	37.56	0.0311
5	S1M2T1	0.9305	37.20	0.0211
6	S1M2T2	0.9541	37.50	0.0248
7	S1M2T3	0.9532	37.30	0.0245
8	S1M2T4	0.9952	37.75	0.0364
9	S2M1T1	0.8340	40.10	0.0114
10	S2M1T2	0.8558	40.13	0.0148
11	S2M1T3	0.8538	40.78	0.0139
12	S2M1T4	0.8740	40.35	0.0176
13	S2M2T1	0.9114	40.75	0.0201
14	S2M2T2	0.9343	40.93	0.0242
15	S2M2T3	0.9318	40.53	0.0238
16	S2M2T4	0.9427	40.55	0.0265

$$\text{Regression Equation: } Y_D = 0.68576 + 14.51242X_A - 170.07381X_A^2$$

* The given values of density, frequency and amplitude are the average values of three replicates.

APPENDIX III: VIBRATOR SCHEMATIC.



APPENDIX IV: SOIL ORGANIC MATTER CONTENT

Soil Type	Organic Matter Content (4)*	Legal Location
Sandy Loam	4.8%	SW20-42-25-W4
Silt Loam	4.1%	SE25-51-24-W4

* Total Carbon (mainly organic carbon) using Leco Induction Furnace.

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